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Fighting global warming by climate engineering: Is the Earth radiation management and the solar radiation management any option for fighting climate change?

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ABSTRACT

The best way to reduce global warming is, without any doubt, cutting down our anthropogenic emissions of greenhouse gases. But the world economy is addict to energy, which is mainly produced by fossil carbon fuels. As economic growth and increasing world population require more and more energy, we cannot stop using fossil fuels quickly, nor in a short term.

On the one hand, replacing this addiction with carbon dioxide-free renewable energies, and energy efficiency will be long, expensive and difficult. On the other hand, meanwhile effective solutions are developed (i.e. fusion energy), global warming can be alleviated by other methods.

Some geoengineering schemes propose solar radiation management technologies that modify terrestrial albedo or reflect incoming shortwave solar radiation back to space.

In this paper we analyze the physical and technical potential of several disrupting technologies that could combat climate change by enhancing outgoing longwave radiation and cooling down the Earth. The technologies proposed are power-generating systems that are able to transfer heat from the Earth surface to the upper layers of the troposphere and then to the space. The economical potential of some of these technologies is analyzed as they can at the same time produce renewable energy, thus reduce and prevent future greenhouse gases emissions, and also present a better societal acceptance comparatively to geoengineering.

Contents

Abbreviations: AVE, atmospheric vortex engine; BC, black carbon; CCS, carbon capture and sequestration; CDR, carbon dioxide removal; CE, climate engineering; CSP, concentrated solar power; DET, downdraft energy towers; ERM, earth radiation management; GE, geoengineering; GH, greenhouse; GHG, greenhouse gases; GW, global warming; HMPT, Hoos mega power tower; IPCC, Intergovernmental Panel on Climate Change; MR, meteorological reactors; *OTEC*, ocean thermal energy conversion; PCM, phase change materials; SCPP, solar chimney power plant; SRM, solar radiation management; SRM, sunlight reflection methods; URE, unusual renewable energies; UV, ultraviolet

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1. Introduction

The most serious and important problem humankind has ever had to face might be global warming with disastrous consequences and costly adverse effects [1]. Adaptation and mitigation strategies might not be sufficient. In May 2013 the CO_2 concentration in the Earth's atmosphere officially exceeded 400 ppm, according to the Mauna Loa Observatory in Hawaii, which has been monitoring atmospheric CO_2 since 1958 when that figure was around 320 ppm. At the time the Intergovernmental Panel on Climate Change (IPCC) issued its 2007 assessment [2], it recommended to keep atmospheric greenhouse gases below 450 ppm in order to keep the temperature rise under a 2 °C target [3].

Many scenarios have been considered in order to slowly decrease our greenhouse gases (GHG) emissions to try to keep the average temperature heat rise under +2 °C. But without an international agreement signed by the biggest polluters, this $\leq$2 °C figure will remain only empty words and will not be followed by actions and effects.

Human GHG emissions have already been so important and some of these GHG have such extraordinarily long lifetimes that even if by a magic wand we could stop all emissions overnight, the average temperature of Earth would continue to rise or stay at current levels for several hundred years [4].

Global warming results from the imbalance between the heat received by the Earth and, the heat reradiated back to space. This paper proposes methods to increase the IR radiation to space. The surface outgoing longwave radiation is defined as the terrestrial longwave radiative flux emitted by the Earth's surface beyond the 3–100 μm wavelength range. The shortwave incoming solar radiation also called global irradiance or solar surface irradiance [5] is the radiation flux density reaching a horizontal unit of Earth surface in the 0.2–3 μm wavelength range. Both are expressed in W m^{-2}.

The GHGs trap some heat and, by greenhouse effect, warm the Earth surface. Incoming and reflected shortwave sunlight patterns are represented on the right side of Fig. 1 from NOAA [6] (inspired by Kiehl [7] and Trenberth [8]); outgoing infrared or longwave radiation modes are symbolized on the left side. The Earth's energy budget expressed in W m^{-2} is summarized in this figure. The principal atmospheric gases ranked by their direct contribution to the greenhouse effect are [7] water vapor and clouds (36–72%), carbon dioxide (9–26%), methane (4–9%) and ozone (3–7%).

Tackling climate change will require significant reductions in the carbon intensity of the world economy. Developing new low-carbon technologies and adopting them globally is therefore a priority. But even moving relatively quickly toward a carbon-neutral economy will still result in a net increase in CO_2 in the atmosphere for the foreseeable future. It seems that we are nowhere close to moving quickly in this direction: gas and fossil fuel reserves have effectively increased, due to improved technologies for extraction. Huge underwater oceanic reserves of methane hydrates or clathrates [9,10] will possibly become extractible in the near future. The recent shale gas boom in USA and the methane reserves do not militate in favor of a reduction of the energy consumption, nor in a reduction of CO_2 and CH_4 emissions. With gas prices hitting rock bottom, the cost competitiveness of renewable energies in the short- to mid-term will be harder to meet than ever before. This has brought further uncertainty about the future of solar projects and offshore wind technologies,

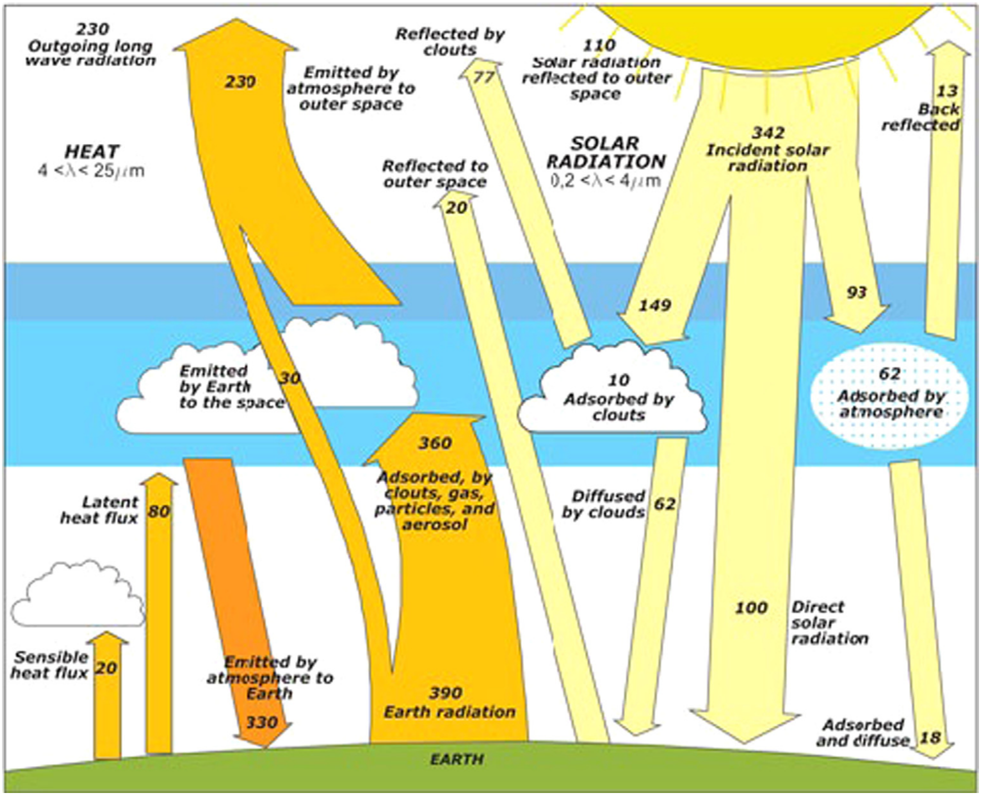


Fig. 1. "Earth's Annual Global Mean Energy Budget" (from NOAA) [6].

particularly solar ones. The innovation challenge spans the development of new unusual renewable energies based on low-carbon technologies as well as – and possibly even more pressing – improving the performance, the efficiency, and particularly lowering the costs of the existing ones.

This review intends to be an element that provides an update on proposed solutions to the control and the management of the climate, and to propose a tool of choice among new and innovative ones.

Geoengineering aims at stabilizing the global climate, reducing global warming and fighting anthropogenic climate change owing to two strategies: shortwave (0.3–3 μm) sunlight reflection methods and carbon dioxide removal technologies. After a short overview of a set of geoengineering strategies, this paper then proposes innovative methods for increasing outgoing terrestrial (4–100 μm, and most often 4–25 μm) radiant energy fluxes by thermal longwave radiation methods. One of the main ideas developed in this review is that GHGs are good insulators that prevent normal interactions with the Earth atmosphere with the space, and keep the Earth too hot, so "atmospheric thermal bridges" have to be created. By analogy to the expression of "thermal bride" used in civil engineering where heat is transferred by conduction from one part of a building to another, with the result of a cooling of the hotter part, we define an atmospheric thermal bride has a way to transfer longwave radiation from one part of the atmosphere (generally the Earth surface) to another (generally in the higher troposphere, the stratosphere, or to the open space). One natural phenomenon illustrating this concept is the atmospheric window, by which IR radiation in the range 8–13 μm can escape directly to space.

After an overview of the principal geoengineering techniques of solar radiation management (SRM or sunlight reflection methods), we present in this review technological breakthrough alternatives, many of them are little known, misunderstood or ignored, that can decrease or decelerate global warming (GW), and also might help to cool the Earth surface.

A 30 years power-purchase agreement of the Southern Californian Public Power Authority [11] for the construction of the first solar updraft chimney in La Paz County, Arizona, USA was announced in February 2011. Another company [12] published plans to combine downdraft evaporative cooling towers with wind towers to produce electricity. The opportunity to take stock of similar disrupting technologies and their benefits is examined in this paper.

These recent announcements for the construction of industrial scale power plants of solar updraft chimneys and downdraft energy towers have been made. These unusual renewable energy power plants belong to the family of large scale power stations called by us "meteorological reactors" which can convert heat into artificial wind inside a duct and produce electricity by driving turbines. Despite many interesting advantages such as the low cost of the kWh produced, a long lifespan, clean energy production and environmentally friendly operations with almost no maintenance, their current commercial applications are limited because of their large initial investment cost and low conversion yield.

Several energy-neutral ideas and techniques will be described, followed by a description of a number of innovative and unusual renewable energies (UREs), from the family of the meteorological reactors (MR), which can at the same time help cooling the planet by Earth radiation management (ERM), produce CO_2-free electricity and prevent further CO_2 emissions.

This review focuses on using several MR, night sky radiation and giant heat pipes as active heat transfer tools to cool down the Earth by artificial vertical wind generation and, at the same time, production of sustainable CO_2-free renewable energy without the drawbacks of current climate engineering strategies. This review sheds light on innovative activity and innovation dynamics in heat-transfer technologies and CO_2-free renewable energy production.

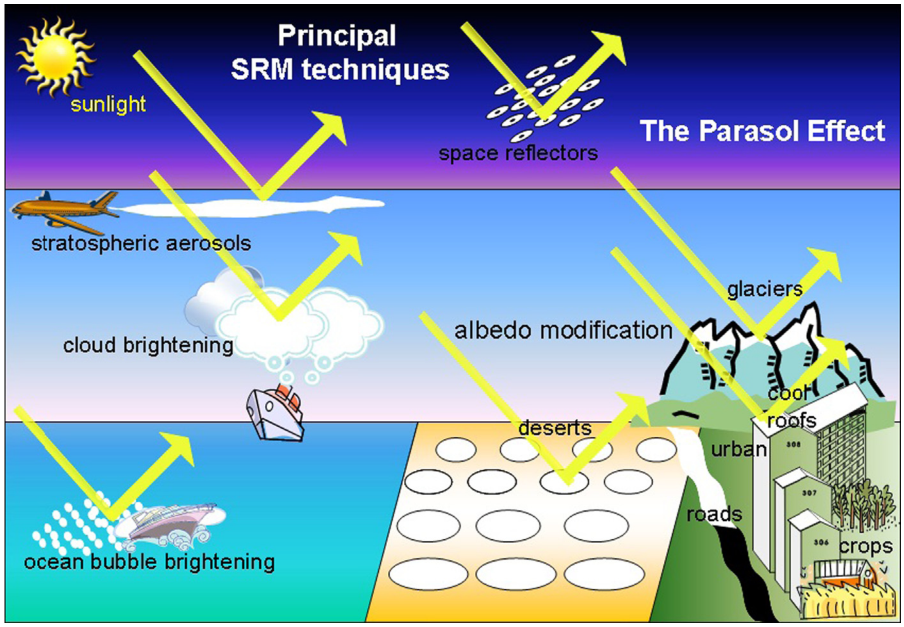


Fig. 2. Overview of the principal SRM geoengineering techniques that attempt to increase the reflection back to space of the incoming solar radiation. These techniques are often referred as acting by a "parasol or umbrella effect".

2. Overview of the major SRM geoengineering proposals

Proposals for GE projects can mainly be divided into two categories: SRM and carbon dioxide removal (CDR) [13]. CDR techniques (that curiously are considered as CE, but probably might not) are out of the scope of this paper and thus will not be depicted. The IPCC Fourth Assessment Report [14a] defines geoengineering (GE) as "*technological efforts to stabilize the climate system by direct intervention in the energy balance of the Earth for reducing global warming*". Geoengineering [15] or climate engineering (CE) consists in a large set of technologies that deliberately reduce solar insolation or increase carbon removal directly from the atmosphere, on a large scale, with the aim of minimizing, counteracting, mitigating, limiting, counterbalancing or reversing anthropogenic climate change in order to reduce GW or its consequences. The raise of geoengineering on the scientific and policy agenda is no doubt at the international level, as it has been assessed by the 5th IPCC working groups (WP) 1 and 3. The 5th IPCC report of WP1 issued in September 2013 [14b] cites geoengineering 50 times only in its chapter 7 and 16 publications on geoengineering are cited in Chapter 6.

In a Royal Society [16] report, geoengineering is defined as the "*deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change*". This Royal Society report reviews a range of proposals aimed to reflect the Sun's rays back to space, and, among means to remove CO_2 from the air for instance oceanic carbon sequestration, by injecting iron into the world's seas to rapidly increase the amount of phytoplankton that feeds itself from CO_2.

An almost exhaustive list of proposed GE projects has been established [17], a very large review of CE proposals has been given by Vaughan [13], and numerous other strategies have been listed [18,19]. Literature is now abundant about geoengineering proposals, describing them in detail and discussing their advantages, effectiveness, potential side effects and drawbacks [16,20,21,22], but also governance, legitimacy and ethical aspects [23,24,25]. As a matter of fact, criticism about CE research focuses on international consequences of possible unilateral use of GE techniques [26,27].

SRM proposals aim to reduce GW by reducing the amount of light received on the Earth and by its atmosphere [28]. It includes (Fig. 2) several techniques like space solar reflectors; stratospheric injection of aerosols; seeding tropospheric clouds by salt aerosols or ice nucleation to make them whiter and also surface albedo change (urban, rural, or atmospheric approaches). Numerous other strategies have been proposed [29,30], but the aim of this review is not to be exhaustive. GE has been quite studied since 2008 and is envisioned as a plan B in case the governments do not succeed to reduce CO_2 emissions. At the international level of climate change politics, the positioning of CE as an option between mitigation and adaptation is taking concrete form. The elaboration of an alternative plan C developing the concept of Earth radiation management (ERM) is at least appealing and entailing and is the goal of this review which has in mind the need for innovative breakthroughs. Those new strategies have the potential to address 2.2 times more energy flux (69%) than SRM (31%).

2.1. *Space mirrors [31,32] and science fiction-like proposals*

The idea of this GE scheme is to send into orbit giant mirrors (55,000 orbiting mirrors each of 100 km^2) made of wire mesh; or to send trillions of light and small mirrors (the size of a DVD), in order to deflect sunlight back to space. In other words numerous artificial mini-eclipses that will obscure the sun. This option is widely considered unrealistic, as the expense is prohibitive, the potential of unintended consequences is huge and a rapid reversibility is not granted.

Similarly, the reduction of incoming solar radiation was considered by placing a deflector of 1400-km diameter at the first Lagrange Point, manufactured and launched from the Moon [33]. The idea to mine the moon [28] to create a shielding cloud of dust is in the same league.

Several other proposals have been studied and discussed by some scientists but, at our knowledge, not by the space industry which probably fears that the thousands of orbiting debris could damage the satellites in orbit.

2.2. *Sulfate aerosols [34,35]*

This scheme is inspired by studies of the Mount Pinatubo volcano eruption in the Philippines in 1991 and by the cooling

Table 1
Estimates of the cooling potential of several geoengineering techniques by Lenton and Vaughan [13] and the Royal Society report [16] (includes CDR techniques not discussed in this paper).

Geoengineering technique	Cooling potential
Stratospheric aerosols	3.71
Albedo increase of clouds, mechanical	3.71
Albedo increase of deserts	1.74
Air capture and storage	1.43
Ocean phosphorus addition	0.83
Albedo increase of grassland	0.64
Bio-char production	0.52
Carbonate addition to oceans	0.46
Albedo increase of croplands	0.44
Ocean nitrogen fertilization	0.38
Iron fertilization	0.29
Afforestation	0.27
Albedo increase by human settlement	0.19
Enhance upwelling	0.028
Albedo increase of clouds by biological mean	0.016
Enhance downwelling	0.016
Albedo increase in urban areas	0.01

effect of its sunlight blocking sulfur plume. This "artificial-volcano" idea is one of the least costly, and very small sulfate particles in the stratosphere could last for a couple of years. The two main problems are acid rain creation and probable damage of the ozone layer.

But, currently burning fossil fuels and coal in particular and other anthropogenic emissions, already introduce every year nearly 110 million tons of SO_2 in the lowest levels of the atmosphere [36]. With other reflective tropospheric aerosols this has a direct cooling effect evaluated by Hansen [37] to 1 W m^{-2}, plus an indirect cooling effect of 0.8 W m^{-2}. Not all these aerosols are anthropogenic and volcanic aerosols also tamped down Earth warming: recent work from Neely [38] revealed that moderate volcanic eruptions, rather than Asian anthropogenic influences, are the primary source of the observed 2000–2010 increases in stratospheric aerosol. Sulfates in the troposphere have a much shorter resilience time than those in the stratosphere, that is why 1–5 million tons of small size particles of SO_2 in the stratosphere every year [39] would have a more efficient cooling effect than current emissions in the troposphere.

Reducing the sulfates emissions from power plant, as is already done in the US, Europe and Japan, is helpful for reducing acid rain, but it removes the umbrella of sulfates protection that reflects solar radiation back to space and shields the Earth from the warming effect of GHGs and thus has a net warming effect. The problem is complex but if by magic tomorrow it was possible to stop completely burning coal, the result would be an immediate major global warming effect.

This paradoxical existing incentive in favor of non-reduction of pollution could be a possible rationale for promoting SRM in spite of the moral dispute over GE. But to become morally acceptable, SRM should be limited to the idea of compensating for the warming effect of local air cleaning. SRM should not be aimed to substitute to the needed efforts of GHG emissions down-curving, as CO_2 levels will continue to rise in the atmosphere soon breaking the 450 ppmv level limit climatologists recommend, to eventually reach 800 ppmv or even more.

Among several other critics [40] to the use of sulfates in the stratosphere, there is the need to deliver every year at least one million ton of SO_2 using thousands of balloons, planes or rockets, costing between $25 and $50 billion annually and having to be maintained continuously. Also a change in overall rain patterns and a non-uniform cooling effect obtained over the entire Earth with winners and losers is among the drawbacks, together with the non-resolution of the problem of ocean acidification.

The addictive character of this techno-fix will not encourage decreasing our CO_2 emissions and if stopping this geoengineering scheme was mandatory for whatever reason (unexpected effects, financial crisis…), the stratospheric sulfate sunshade would rapidly lift and several decades′ worth of warming would hit the Earth and all living organisms with no left time for adaptation.

One of the greatest fears for the opponents to CE comes from the fact that due to the relatively low cost of SRM (compared to CDR) and potential to act quickly (e.g. like after the Pinatubo eruption), SRM may be adopted by some governments without consulting other countries, as in this particular case national policies have international effects. GE attempts made by some countries may conduct their neighbors to perceive them as rogue states. The fair amount of the current research on governance of GE might unintentionally convince that if appropriate governance frameworks, principles and codes are in place thus developing GE options can be a responsible option. The debate about governance, legitimacy and ethics cited early [23,27] is still mostly centered on the sulfate aerosol option.

2.3. *Cloud whitening [41,42]*

The idea is that sea water can be pumped up and sprayed into the air to increase the number of droplets, and produce fine sea salt crystals increasing the reflectivity of low altitude clouds. Together, many droplets and salt aerosols are expected to make whiter clouds and reflect more intensity of sunlight. It seems harmless and not too expensive, but needs to be done on a huge scale to have any global effect. This proposal (and several others) is backed financially by former directors from Microsoft. According to Latham [43], in the first decades of operation, the amount of disseminated salt over land would be several orders of magnitude less than naturally produced. This mechanism is based on the Twomey and Albrecht effects: increasing number or surface area of droplets increases the scattering of light, thus increasing albedo. As reducing droplet size lowers their sedimentation velocity, precipitation could be delayed or inhibited, increasing cloud lifetime, so there will be an increased cloudiness.

A "Flettner" rotary ship using the "Magnus effect" is studied by Salter and Latham [41,43] for spaying sea water aerosols.

If a meaningful amount of tankers and fleet of commercial vessels was equipped to vaporize small droplets of salted water for cloud whitening as experimented by Salter, the SRM effect could become regular, global and at low cost. For Latham [43] 1500 spray vessels can produce a negative forcing of -3.7 W m^{-2}. If any unforeseen adverse effect occurs, the reversibility is rapid, as the system can be switched off instantaneously and in a few days the clouds properties will return to normal. This technology produces local cooling and can also reduce the intensity and severity of hurricanes.

A similar technique has been proposed by Seitz [44] using the vessels of the commercial fleet to inject micron-size bubbles in the oceanic waters in order to increase albedo and cool the water.

2.4. *Other albedo changes [45,46]*

The proportion of light reflected from the Earth′s surface back to space is called albedo after the Latin word *albus* for white. In the Earth radiation budget it is identical to the outgoing shortwave radiation, with spectral properties in the range of those of the incoming light from the sun.

Road asphalt is hotter during the summer, meanwhile white roofs stay cooler [47], allowing saving some electricity used for air conditioning and thus avoiding CO_2 emissions. According to Akbari

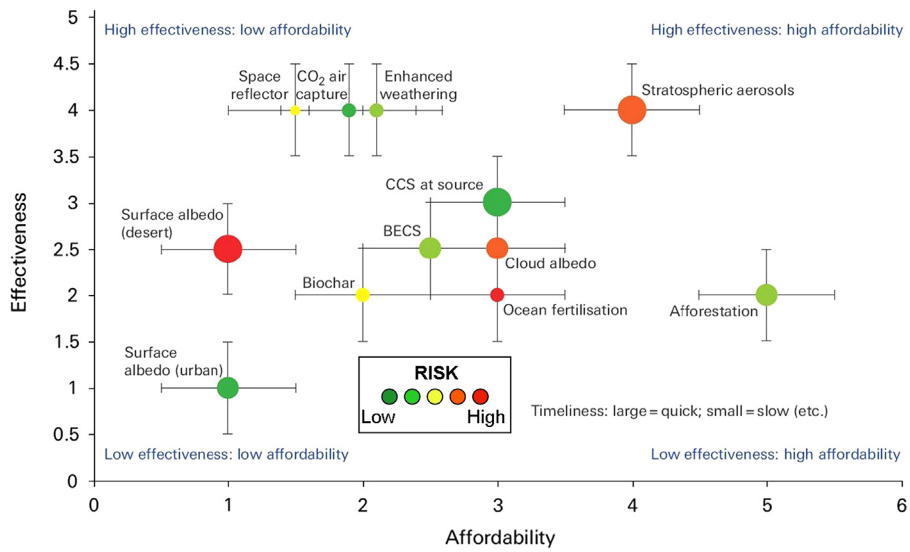


Fig. 3. Geoengineering proposals classified in the Royal Society report [16] for their safety, effectiveness and affordability.

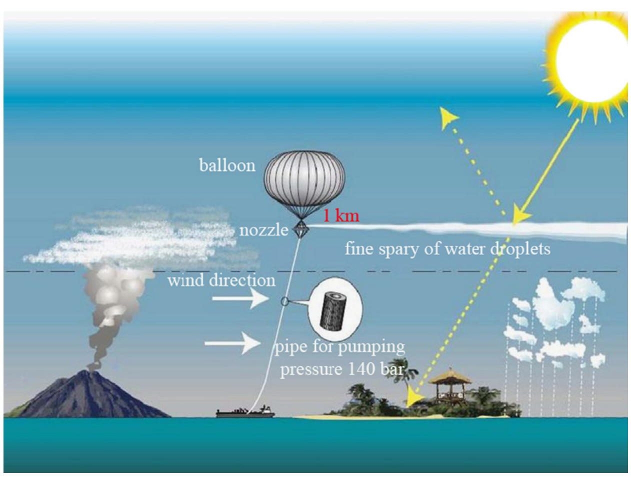


Fig. 4. The SPICE experiment [58]a-b

[45], replacing 1000 ft^2 (93 m^2) of a dark roof by a white roof, might offset the emission of 10 t of CO_2 (air conditioning savings and albedo effect). Several companies have developed asphalt road coatings and asphalt roofs coatings that reduce surface heat by up to 15–20 °C and thus the urban heat island effect.

Painting roofs and roads in white, covering glaciers and deserts with reflective plastic sheeting, putting white or pale-colored plastic floating panels over oceans or lakes, and planting genetically engineered paler crops have all been proposed to reflect sunlight back into space (Fig. 2). Gaskill [48] gave an extensive overview of rationale, pros and cons of global albedo projects. Replacing tropical forests by high albedo deserts is not an option, but the development and advance of the forests to the North could have a positive retroaction on global warming: in this case, the refusal of a GE scheme (like planting whiter trees) for moral reasons does not seem justified as it fights against a GW positive feedback and also decreases CO_2 atmospheric levels by wood production.

Boyd [49] and then the UK Royal Society [16] evaluated recently and ranked the main SRM and CDR techniques for their safety, effectiveness, affordability and cooling potential (calculations details inside the report). Table 1 and Fig. 3 from the Royal Society report summarize their findings.

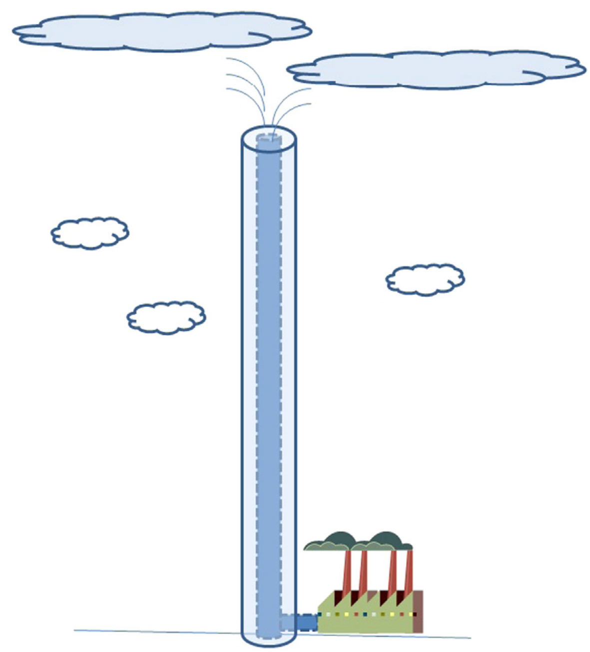


Fig. 5. Kilometric high conduit for aerosol spraying in the stratosphere [60].

Air capture consists to capture diluted CO_2 in air with alkaline polymers and BECS consists to produce bio-energy followed by carbon storage.

The 2005 IPCC special report on carbon capture and sequestration (CCS) [50] provides a full description of these technologies. CDR and CE techniques have been reviewed elsewhere [13,16,51] and will not be mentioned here.

2.5. Some examples of small scale SRM experiments already performed

It is worth pointing out that several small scale field SRM studies, or experiments have already been carried out, or are planned, but with no global GE aim. Some are isolated or individual initiatives, with different levels of maturity and

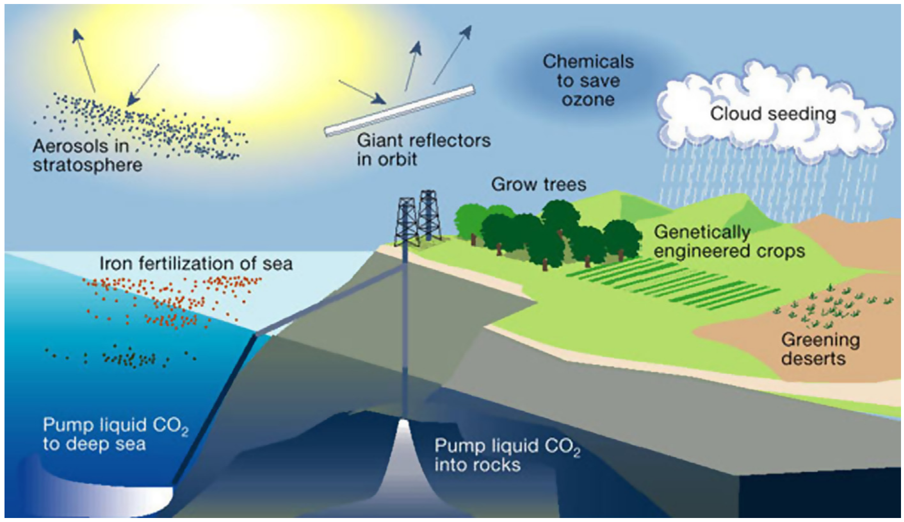


Fig. 6. Several geoengineering schemes as represented by Matthews [67].

sophistication, many without scientific research purposes, but they have received some public attention, for instance:

- In 2005 a small pilot project on the Gurschen glacier of the Swiss Alps was conducted to try to stop the ice melting of glaciers [52a] with a "ice protector" textile made of a lightweight dual-layer composite with polyester in the top side to reflect light, and polypropylene on the bottom to block heat and slow ice melting during the summer. It proved successful as the blanketed area had 80% less melt than surrounding ice. Covering an area of 30,000 m^2 was projected on the Vorab glacier.
- In the Peru Andean region, a local team that painted rocks in white won a $200,000 prize from the World Bank as part of its "*100 Ideas to Save the Planet*" competition [52b–c]. Meanwhile the "Fund for Innovative Climate and Energy Research" is financed by Gates [52d] and is more devoted to SRM projects, the "Virgin Earth Challenge" financed by Brandson [52e] is more concentrated on CDR and offers a $25 million prize for a commercially viable invention able to permanently remove significant volumes of GHGs out of the Earth's atmosphere, so as to contribute materially to avoid global warming.
- In cold countries, with winter freezing rivers [53] and lakes it can be drilled bore holes into the ice that has started to form. The water will be discharged across the surface, where it will freeze and add layers of ice rinks. The ice cap itself being a good insulator, if no holes were drilled in it, much less water would freeze. This process could be repeated at regular intervals throughout the winter with the aim to produce a big block of ice several meters thick as refrigeration storage, to cool and water the cities as it melts during summer. The insulation capacity of the ice is broken by one of the "thermal bridge" strategies that will be developed later.
- Over the summer months, up to 40–50% of the water stored in small farm dams may be lost to evaporation, but using white reflective covers to reduce this loss increases agricultural water use efficiency and participates to global cooling by modifying albedo [54].
- Rising salty groundwater currently threatens many agricultural lands, but a salinity mitigation strategy[55] is already applied in Australia. The aim is to prevent the clear ground water to mix with the salty one, and consisted during the dry season in pumping salty groundwater into shallow evaporation basins to form a salt pan with higher reflectance than the surrounding farmland which resulted in an immediate mitigation of local warming both by evaporation and by albedo modification. The main goal is achieved too: preventing salty ground water to mix with the clear one.
- The SPICE project [56]a–b (stratospheric particle injection for climate engineering) consisted in using a small hose-augmented balloon up just over one km high, pumping water into the air. The aim was to test the feasibility of later piping sulfates at 25 km high (see Fig. 4). Although only water was to be sprayed, GE opponents succeeded to stop this experiment. Partanen [57] showed that multiplying the mass flux by 5 or reducing the injected particle size from 250 nm to 100 nm could have comparable effects on the GE radiative efficiency.

In 2002, an artificial cloud making method was patented in China [59]. It replicates Earth's Hydrologic Cycle, using a pipeline facility constantly conveying air, from a lower altitude to a higher altitude, with water vapor which condenses to form a pervasive artificial cloud. More recently several US patents [59] from former Microsoft scientists described a very similar concept, with a 15–50 km high altitude duct "conduit" like in Fig. 5 for the aerosol injection in the stratosphere. That sounds quite high, but several articles from NASA describe the feasibility of multi-kilometer height tall towers [61–65]. Later in this review, some ERM strategies propose to make use of quite high meteorological reactors, but civil engineers and architects are confident on their feasibility, as already almost kilometric high buildings have been successfully built and numerous projects all over the world target taller ones.

2.6. Discussion about SRM

SRM methods may be able to reduce temperatures quickly and some of them like stratospheric aerosols at comparatively low cost. However, even if they could reduce some of the most significant effects of global warming and lessen some of its harmful impacts, these technologies could also have significant unanticipated harmful side effects. Moreover, they would not eliminate the cause of climate change, the emissions of GHGs and the associated threat of ocean acidification. For many experts the whole idea of pursuing these "technical fixes" is controversial since SRM can probably restore on average the Earth's global radiative balance, but regional climate discrepancies will remain [66].

Also, if CO_2 levels continue to rise during SRM, that means it must be maintained indefinitely to avoid abrupt and catastrophic

warming and there must happen no technological, economical or political failure.

In a position where avoidance of one danger exposes one to another danger, CE has been widely shunned by those committed to reducing emissions and by the public which feels that SRM and GE (often only associated to sulfate aerosols) is far too risky to attempt, since tampering with Earth′s and climate systems could lead to new climatic and ecological problems.

The principal GE schemes are represented in Fig. 6 reproduced from Matthews [67]. In a paper whose title is "*Can we test geoengineering?*", MacMynowski [68] noted that SRM tests could require several decades or longer to obtain accurate response estimates, as the hydrological and temperature responses will differ from a short-duration test and also from what has been observed after large volcanic eruptions. Robock [40] found "*20 reasons why geoengineering may be a bad idea*".

By pumping massive amounts of CO_2 and other GHGs into the atmosphere and by building mega-cities and thousands of kilometers of black paved highways, humans have already engaged in a dangerous geophysical experiment. The only difference with CE is that it was unintentional. The best and safest strategy for reversing climate change is to halt this buildup of atmospheric GHGs and stop CO_2 emissions, but this solution will take time, and it involves a myriad of practical and political difficulties. Meanwhile, the dangers are mounting and even with a serious effort to control GHGs emissions, meaningfully reducing them in the very near term is an unattainable goal.

As Myhrvold and Caldeira [69] showed, the rapid deployment of low-emission energy systems can do little to diminish the climate impacts in the first half of this century: conservation, wind, solar, nuclear power, and possibly CCS appear to be able to achieve substantial climate benefits only in the second half of this century.

So maybe GE will be needed, although serious research on CE is still in its infancy, and till recently has received little financial funding for scientific evaluation of benefits and risks.

But even if the ethics of geoengineering as well as political aspects has been widely discussed [20–27], neither international nor public [70,71] consensus has been yet obtained even for research on this subject: stopping the "spice experiment" previously cited is an illustration.

It is worth noting that since 1977 there is an Environmental Modification Convention, which has so far been ratified by 76 countries [72]. It prohibits the hostile use of techniques that modify the dynamics, composition, or structure of the Earth (including the atmosphere) or of outer space. One of the main questions of the debate is: in a fragile and globalize world, who would govern geoengineering actions that can severely affect climate and, for this reason, might be potentially used as weapons?

Also, till date the most successful international agreement is the Montreal Protocol on Substances that Deplete the Ozone Layer [73] that was agreed in 1987. It included trade sanctions to achieve the stated goals of the treaty and offers major incentives for non-signatory nations to sign the agreement. As the depletion of the ozone layer is an environmental problem most effectively addressed on the global level the treaty include possible trade sanctions, because without them there would be economic incentives for non-signatories to increase production of cheap depleting substances, damaging the competitiveness of the signatory nations industries as well as decreasing the search for less damaging alternatives. All UN recognized nations have ratified the treaty and continue to phase out the production of chemicals that deplete the ozone layer while searching for ozone-friendly alternatives. In the presence of halogenated compounds, the sulfate aerosols in the stratosphere might damage the ozone layer [39] thus this SRM might be a violation of the Montreal Protocol spirit and goal.

The intergenerational transfer of atmospheric carbon and GHGs stocks and pollution is also part of the discussions [74,75] as this is equivalent to delay current generation′s abatement efforts. Future generations will have to limit the damages of the atmospheric carbon stock that they will inherit from current society. Together with radioactive nuclear wastes, this implies future costs and a poisoned chalice to leave to our heirs and successors.

In the absence of adequate reductions in anthropogenic CO_2 emissions, GE has been put forward as the only remaining option that might fix our rapidly changing climate, even if scientists are reluctant to encourage governments to deploy CE rather than invest in cutting emissions and making efforts to control them.

CDR and CCS techniques address the root cause [16] of climate change by removing the most abundant GHGs from the atmosphere, but will require decades to have significant effects. SRM techniques are much faster (months) and attempt to offset the effects of increased GHGs concentrations by reducing the absorption of solar radiation by the Earth. Both methods have the same ultimate aim of reducing global temperatures.

3. Earth radiation management (ERM)

Proposed SRM GE schemes act by the parasol effect: reducing solar incoming radiation. However CO_2 traps heat both day and night over the entire world whereas diminished solar radiation would be experienced exclusively in daytime and on average most strongly at the equator.

The technologies described in this paper, although seasonal, are expected to be less intermittent and cover more than the diurnal cycle and are well distributed from equator to pole as they are complementary. Fig. 7 shows on which radiation fluxes SRM geoengineering schemes might be useful acting on shortwave radiation (0.2–3 μm), which represents less than 1/3 of the total incoming radiation. ERM proposed in the next part of this review focuses on more than 2/3 of the global radiative budget and is possible night and day all over the Earth. The goal of this paper is to demonstrate that several other ways of action are possible acting on the longwave radiation (4–25 μm) flux.

3.1. Targeting high and cold cirrus clouds: not a SRM strategy but a ERM one

Mitchell [76] proposed to cool the Earth surface by increasing outgoing longwave radiation by reducing the coverage of high cirrus clouds.

Cirrus clouds tend to trap more outgoing thermal radiation than they reflect incoming solar radiation and have an overall warming effect. As they have a greater impact on the outgoing thermal radiation, it makes sense to target the colder cirrus clouds. This proposal consists in increasing outgoing longwave radiation by dispersing clouds over the polar ice caps. Thus by changing ice crystal size in the coldest cirrus, outgoing longwave radiation might be modified. According to Mitchell, the coldest cirrus have the highest ice super-saturation due to the dominance of homogeneous freezing nucleation, so seeding cold cirrus (high altitude) with efficient heterogeneous ice nuclei (like bismuth tri-iodide BiI_3) should produce larger ice crystals due to vapor competition effects, thus increasing outgoing longwave radiation and surface cooling. BiI_3 is non-toxic and Bi is one order of magnitude cheaper than Ag (sometimes used to increase rainfall).

Preliminary estimates by Mitchell [76a,b] and by Storelvmo [76c] show that global net cloud forcing could neutralize the radiative forcing due to a CO_2 doubling. Airline industry is the potential delivery mechanism for the seeding material and reversibility should be rapid after stopping seeding the clouds.

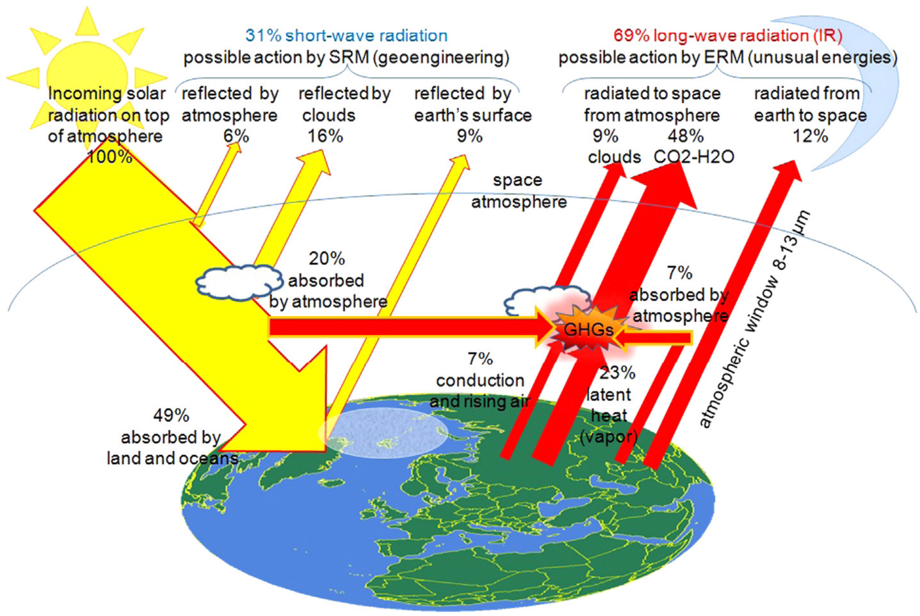


Fig. 7. Principal energy fluxes in yellow the ones corresponding SRM geoengineering schemes, and in red the others concerned by the sustainable ERM proposed new ways of action (i.e. increase sensible and latent heat transfer to the outer space).

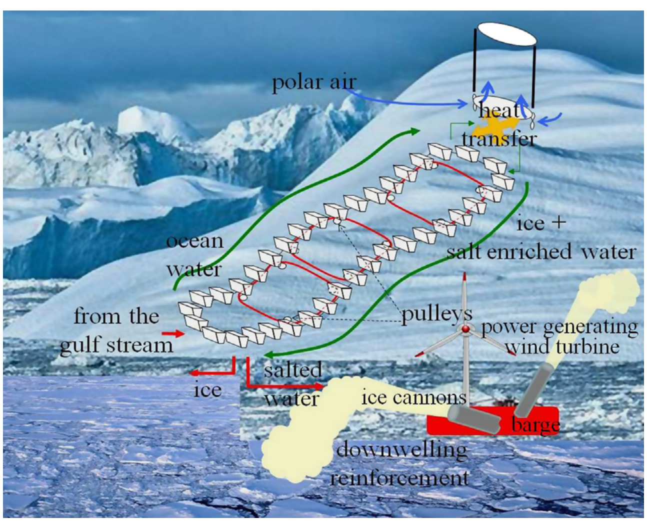


Fig. 8. Representation of two EMR strategies. The technology proposed by Zhou and Flynn [77] to re-ice the Arctic during the winter uses ice cannons powered by wind turbines floating on barges, and the technology proposed by Bonnelle [78] consists in transporting sea water till the top of northern mountains where the air is very cold and just before freezing carrying it back downhill to the ocean where floating ice and saltier water are released.

This approach would not stop ocean acidification, buts seems to have less drawbacks that stratospheric injection of sulfates.

3.2. Preventing a possible weakening of the downwelling ocean currents: also an ERM strategy?

The formation of North Atlantic Deep Water releases heat to the atmosphere, which is a contributor to a mild climate in Europe. Without the warm North Atlantic Drift, the UK and other places in Europe would be as cold as Canada, at the same latitude. But the increase of CO_2 in the atmosphere might produce a weakening of the North Atlantic Deep Water by modification of downwelling ocean currents. The slowdown of new sea ice formation might lead to the abatement of the thermohaline circulation. With the aim to prevent it, Zhou and Flynn [77] assessed the costs of several methods for enhancing downwelling ocean currents, including the use of existing industrial techniques for exchange of heat between water and air. They proposed the use of snow-cannons powered by wind turbines on floating barges during the winter to help the formation of thicker sea ice by pumping ocean water onto the surface of ice sheets. Sea ice that forms naturally in the ocean does so at the bottom of an ice sheet and is not very salty (ice rejects the salt as it freezes). As sea ice formation increases the salinity (salt content) of the surrounding water, this cold and salty water is very dense, and sinks creating the “global conveyor belt”. Zhou and Flynn make the assumption that if seawater freezes on top of an ice sheet, salt would mainly be trapped on the surface or within the ice, both as brine cells and solid salts, especially if the thickness of ice built up to several meters thick. In this case, then incremental downwelling current would occur when the sea ice melted in the spring, since the melting ice would lower the temperature of seawater and the surrounding ocean salinity would be unchanged. On the contrary, if brine was able to flow from the top of the ice sheet back into the ocean in the winter as incremental sea ice will be formed, then incremental downwelling current would occur in the winter driven by salinity. In both cases the goal of enhancing downwelling ocean currents is reached.

Of course on the one hand the Zhou and Flynn proposal can be classified in the albedo modifications schemes of the SRM strategies (Fig. 8), as it participates in maintaining the polar ice caps which help to regulate global temperature by reflecting sunlight.

But on the other hand their strategy can also be evaluated differently. As the first layers of floating ice are good thermal insulators, natural heat transfer from the winter cold air to the liquid water under the ice is not very efficient, so the growth of the ice caps is slow and the increase of the thickness limited. The Zhou and Flynn strategy overpasses this problem, and they obtain a thicker ice cap that can last longer in spring and thus reflect more sunlight back to space. But also, during the winter manufacture of the ice by sending a seawater spay in the cold air, the latent heat of solidification (freezing) will be released in the atmosphere: cold ice is created on the ocean surface meanwhile the hot air generated, will by natural buoyancy go upper in the troposphere. So a heat transfer from the surface to a higher elevation has occurred. A similar strategy was previously described for rivers

[53] or lakes in cold countries. It is as if a thermal bridge was created by the ice canons between warmer water and cold air to bypass the insulation caused by the first thin ice cap.

Adapting some of the previous processes to slowdown glaciers melting during summer seems possible. Quite often lakes form below melting glaciers. Those lakes hidden under the snow make the risk of giving jog suddenly, releasing large quantities of water and mud. To prevent avalanches and floods in the summer, some cities upstream of these under-glacier lakes install pumping systems for emptying them as they are formed, and water is discharged into rivers. Instead, at night the water could be pumped up above the level where temperatures remain negative and with snow-cannons used to produce new fresh and clean snow with high albedo. This technique also transfers heat from the water to the air. At lower altitudes thermosyphon heat pipes, as well as other mechanisms to facilitate the sublimation of water, can also help to contain the summer glacier melting.

3.3. *Alternatives to SRM do exist*

These last examples show that complementary strategies or approaches to SRM are possible, in particular those targeting infrared radiation out to space. Several ideas concentrating in the Earth radiation management, including latent heat and sensible heat riddance methods and anthropogenic waste heat energy removal means, will be presented in the following paragraph.

In the next chapters, unusual renewable energies (UREs) are described, which can at the same time produce electricity, avoiding the CO_2 emissions that would otherwise have been made by conventional fossil power plants and also help cooling down the Earth. Last but not least, these UREs can also help to avoid the waste heat energy associated with nuclear power plants as well as with almost all other thermal power plants.

4. Why looking for energy removal methods?

4.1. *Waste heat and thermal emissions also warm Gaia*

Human activities are not only releasing GHGs into the atmosphere, but also waste heat at the Earth surface and into the oceans. Fossil fuel powered plants emit most of the GHGs, but also add significant amount of their intake energy as waste heat. Generation of 1 kWh of electricity by a “typical” coal-fired power plant emits 1 kg of CO_2, but also releases about 1.8–2 kWh of low grade heat into the surrounding environment [79] which, although a minor one, is another form of forcing on the climate system. Of course this is on average, as CO_2 emissions depend on technology used (combined cycle, integrated gasification combined cycle, conventional pulverized coal, oxygen combustion…), and also on the type of fuel [95b]. For instance the CO_2 emissions in gCO_2/kWh of electricity produced are 920 for anthracite, 990 for lignite, 630 for crude oil, 400 for natural gas, etc. In 2010, 43% of CO_2 emissions from fuel combustion were produced from coal, 36% from oil and 20% from gas.

The electricity generated both by conventional power plants and by renewable ones is also largely dissipated as waste heat. These anthropogenic heat sources have generally been considered quite small compared with radiative forcing due to GHGs [80]. The Earth thermal energy fluxes from the sun's energy received in connection with GHG and aerosols emissions are represented in Figs. 1 and 7, but power plants in converting energy from thermal to electrical energy also generate waste heat, mostly released at the Earth surface.

For more than a century, scientists had suspected that cities impact rain patterns. Nowadays there is increasing observational evidence [81] that urban land cover can have a significant effect on precipitation variability. The urban heat island, the city structures and the pollution all interact to alter rain storms around cities [82]. Increased temperature may provide a source of buoyant unstable air that rises and the city's buildings provide a source of lift to push warm, moist surface air into the cooler air above it. Thanks to urban aerosols that act as cloud condensation nuclei, this hot humid air can develop into rain clouds that soak the area downwind up to 50–100 km. Large urban areas and urban environment alter regional hydro-climate, particularly precipitation and related convection processes which are key components of the global water cycle and a proxy for changing climate.

Even if the total human-produced waste heat is only about 0.3% of the heat transported across higher latitudes by atmospheric and oceanic circulations, recently the research conducted by Zhang [83] showed that, although the net effect on global mean temperatures is nearly negligible (an average increase worldwide of just 0.01 °C), the waste heat generated by metropolitan areas can influence major atmospheric systems, raising and lowering temperatures over hundreds of kilometers. However, the noticeable impact on regional temperatures may explain why some regions are experiencing more winter warming than projected by climate computer models.

In this paper, Zhang based his calculations on the 2006 world's total energy consumption that was equivalent to 16 TWh (20.4 TWh in 2011 according to the IEA [95c]), of which an average of 6.7 TWh was consumed in 86 metropolitan areas in the Northern Hemisphere, where energy is consumed and dissipated into the atmosphere as heat. The results of the Zhang computer model show that the inclusion of the energy use at these 86 model grid points exceeds 0.4 W m^{-2} that can lead to remote surface temperature changes by as much as 1 K in mid- and high latitudes in winter and autumn over North America and Eurasia.

The effect of waste heat is distinct from the so-called urban heat island effect. Such heat islands are mainly a function of the heat collected and re-radiated by pavement, buildings, and other urban features, whereas the Zhang study examines the heat produced directly through transportation, heating and cooling units, and other activities. The long lifetime of CO_2 and GHGs in the atmosphere and their cumulative radiative forcing are higher than waste heat warming. However the latter may be important for the short-term effects, and the next decades as the growth of total energy production will not stop [84].

According to Nordell [85a,b] heat dissipation from the global use of non-renewable energy sources has resulted in additional net heating. His 2003 paper “*Thermal Pollution Causes Global Warming*” was quite commented [86a–d] but since then, modeling performed by Flanner [87] suggested that waste heat would cause large industrialized regions to warm by between 0.4 °C and 0.9 °C by 2100, in agreement with Chaisson's estimates [88], thus showing that anthropogenic heat could be a minor but substantial contributor to regional climate change, and have local climate effects [89–91].

Besides the GH effect, for later generations the anthropogenic heat release can become dangerous. The UREs presented in this paper can contribute to the growth of global energy production without GHGs emissions, and cooling the Earth instead of warming it.

The global average primary energy consumption (0.03 W m^{-2}) is relatively small compared with other anthropogenic radiative forcing effects, as summarized in the 2007 IPCC report [80]. Nevertheless, despite its relatively small magnitude, power plants waste heat may have a considerable impact on local surface temperature measurements and important potential impact in future climate. Even if our current global primary energy consumption which amounts only to 16 TW and is nothing compared

with the 120,000 TW of solar power absorbed by the Earth, what matters is the balance between how much heat arrives or leaves the Earth. The UREs presented in this paper might cool the Earth at the ground level and not warm it, thus help to maintain the Earth′s energy budget.

4.2. Renewable energies have some dark side

Even renewable energies produce local heat, although they provide a greater thermal reduction benefit by avoiding CO_2 emissions.

Photovoltaic [92] solar panels are mainly black or dark with very low albedo and high emissivity, typically absorbing about 85% of the incoming light, 15% of this is converted into electricity, the remainder 70% of the energy is turned into heat. Millstein [93] found that the large-scale adoption of desert PV, with only 16% albedo reduction, lead to significant local temperature increases (+0.4 °C) and regional changes in wind patterns. Of course several studies have proven the utility of roof PV panels urban cites [94] and the overall balance is positive.

According to IEA [95] the total (dark) collector area of unglazed water collectors for swimming pool represents 18 km^2 in the USA and 4.7 km^2 in Australia. Inside urban environments PV and solar thermal panels for warming domestic water might increase the local heat island effect, because they modify the albedo of the place where they are installed. However, the benefits of PV systems are bigger, as the direct effect of providing local power and the indirect ones as avoiding the use of fossil-fuel power plants (reduced emissions of GHGs and other pollutants, such as ozone precursors and regional improved air quality).

Concentrated solar power (CSP) [96] is a technology where a fluid is warmed by concentrated sunlight and this heat is used to produce vapor and rotate turbines. Depending on the CSP type, the Carnot efficiency is around 15–20%, the remaining energy is released as waste heat.

Some hydroelectric dams might also present some drawbacks in our warming world: in equatorial and tropical regions the anaerobic organic matter decomposition in the reservoirs depths releases methane in the atmosphere [97–99], and methane is a GHG with a global warming potential 25 times higher than for CO_2. Dams also release N_2O which is an ozone depleting gas and also a potent GHG nearly 300 times more harmful than CO_2.

Large dams might also be related to earthquakes [100,101], as well as deep geothermal energy which might be associated with induced seismicity. For instance deep geothermal research led to the cancellation of a project in Basel, Switzerland, after the high-pressure fracturing of rock around the well caused hundreds of seismic events some of them large enough (magnitude 3.4, 2.6 and 2.7) to damage property [102,103].

cOcean thermal energy conversion (OTEC) consists to produce electricity by driving turbines with a hot source and a cold sink, thus pumping warm surface seawater and cold deep seawater through heat exchangers. It works best when the temperature difference between the warmer, top layer of the ocean and the colder, deep ocean water is about 20 °C, or more when possible. Deep injection of heat poses problem, as the heat life expectancy in depth and at the surface is quite different. Depth heat will stay there for years as the thermal resistance between the bottom of the oceans and the biosphere is large, while the surface heat will quickly be ended by exchange with the atmosphere, and with the cold source which is the space by clear sky. As a result, the deep layers of the ocean are warmed and by thermal expansion can add up to the current sea level rise problem due to global warming, which causes floods concerns for coastal cities and low altitude islands. Also, as the amount of energy transferred to the cold source is more than 20 times the work removed from the system, it could be better to develop solar ponds than OTEC: a greater temperature difference can be obtained, with a better Carnot yield, and neither the sea level rise, nor the biodiversity and biotopes modification problems.

If in the near future wind energy manages to represent a significant part of the energy production, large scale wind farms might affect local climate. Keith [104] found that very large amounts of wind power can produce non-negligible climatic change at local and continental scales and Keith also observed some large-scale effects. Wang [105] found that if wind turbines can meet 10% or more of global energy demand in 2100, they could cause surface warming exceeding 1 °C over land installations, but in contrast, surface cooling exceeding 1 °C is computed over ocean installations. Thus, if horizontal man-made surface wind modifications can impact the local climate, why not vertical updrafts? This idea will be developed in the next chapters of this review.

4.3. Can we enhance heat transfer?

In order to cool down the Earth at a global scale several techniques will be proposed in the next chapter as able to enhance heat transfer from the Earth surface to the middle or the top of the troposphere. The rationale can be explained with the help of Figs. 1 and 7. The energy from the sun that reaches the Earth is primarily in the form of visible and near infrared light (although some other wavelengths of the electromagnetic spectrum are also present, as infrared energy (heat) and ultraviolet energy). About 31% of the sunlight (the albedo) is reflected back to space as it reaches the Earth system, by clouds, dust particles, aerosols in the atmosphere, and also by the Earth surface, particularly from snow- and ice-covered regions. About 69% of the sunlight is absorbed by the Earth system (atmosphere and surface) and heats it up; the amount transferred in each direction depends on the thermal and density structure of the atmosphere. Then the heated Earth (land, ocean and atmosphere) will radiate back this heat as longwave radiation, in some cases after having handled it by several processes: dry convection (sensible heat), evaporation (latent heat) and some conduction. But because the Earth system constantly tends toward equilibrium between the solar energy that reaches the Earth and the energy that is emitted to space, one net effect of all the infrared emission is that an amount of heat energy equivalent to ~69% of the incoming sunlight leaves the Earth system and goes back into space in the form of IR radiation (this process is referred as Earth′s radiation budget).

4.4. Earlier computer study

While studying the effect of adding “ghost forcings” (heat source terms), Hansen and Sato [106] noted that the feedback factor for the ghost forcing they applied to the model varies with the altitude of the forcing by about a factor of two. Their study showed that adding the ghost forcings at high altitudes increases the efficiency at which longwave radiation escapes to space. Of course, the analysis of these results will depend on the cloud cover and of the altitude, but their results can be understood qualitatively as follows. Considering ∇T at the surface in the case of fixed clouds, as the forcing is added to successively higher layers, there are two principal competing effects. First, as the heating moves higher, a larger fraction of the energy is radiated directly to space without warming the surface, causing ∇T at the surface to tend to decline as the altitude of the forcing increases. Second, warming of a given level allows more water vapor to exist there, and at the higher levels water vapor is a particularly effective GHG. Nevertheless, the net result is that ∇T at the surface tends to decline with the altitude of the forcing.

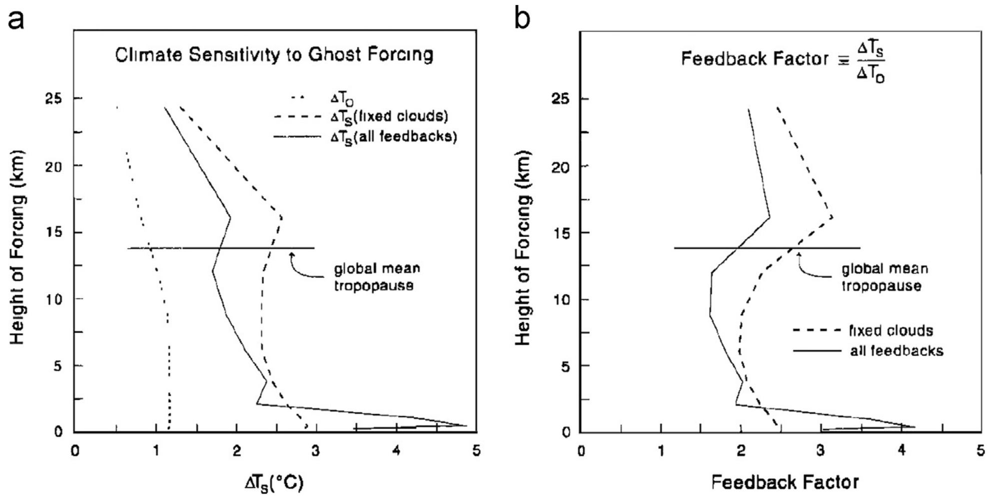


Fig. 9. (a and b) Surface temperature change as a result of a forcing (reproduced from Hansen [106]).

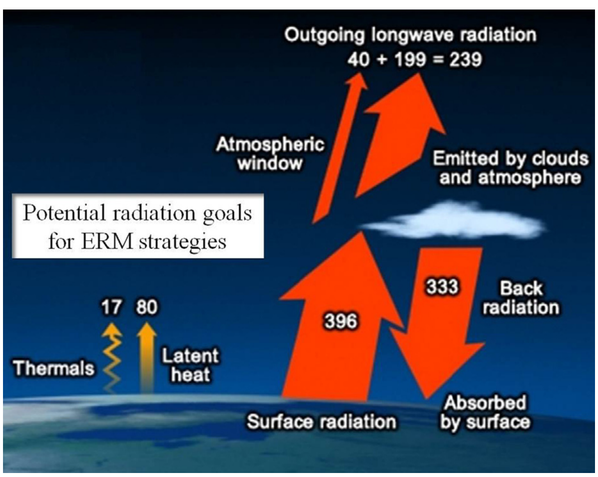


Fig. 10. Outgoing longwave radiation [7,8] types targeted by ERM.

Considering that clouds are free to change, the surface temperature change depends even more on the altitude of the forcing as shown by Fig. 9 from Hansen and Sato [106]. The principal mechanism is that heating of a given layer tends to decrease large-scale cloud cover within that layer. The dominant effect of decreased low level clouds is a reduced planetary albedo, thus a warning; while the dominant effect of decreased high cloud is a reduced greenhouse effect, thus a cooling. However, the cloud cover, the cloud cover changes, and the surface temperature sensitivity to changes may depend on characteristics of the forcing other than altitude (e.g., latitude), so the evaluation requires detailed examination of the cloud changes and was further studied in Hansen's paper.

In Fig. 9a Hansen has represented the surface air temperature sensitivity to a globally uniform ghost forcing of 4 W m^{-2} as a function of the altitude of the forcing. ∇T_0 is the surface temperature response without any climate feedbacks allowed to operate. In Fig. 9b the feedback factor at which the ghost forcing is inserted is represented as a function of the altitude.

4.5. Cooling by irrigation

It is well known that increased evaporation has a cooling influence locally and a warming influence wherever water condenses. It could be anticipated that if water condenses at high altitude, the drier hot air will rise and release part of its energy out to space.

The extent of global warming might have been masked to some extent by increased irrigation in arid regions using ground water and demonstrated by Boucher [107]. For instance Lobell [108] found that, by introducing large amounts of water to the land surface via irrigation, there is a substantial decrease in daytime surface air temperatures during the dry season, with simulated local cooling up to 8 °C and global land surface cooling of 1.3 °C. Each year, irrigation delivers an amount of about 2% of annual precipitation over land, or 2600 km^3 of water to the land surface. Sacks [109] has confirmed local alteration of climate by irrigation, but concluded to an average negligible effect on global near-surface temperatures.

The semi-arid pasture land in Almeria, south-eastern Spain, has been progressively replaced by plastic and glass GHs for horticulture and intensive culture. Today, Almeria has the largest expanse of GHs in the world – around 26,000 ha. Campra [110] studied temperature trends in several regions and found that in the Almeria region, the GHs have cooled air temperature by an average of –0.3 °C per decade since 1983, meanwhile in the rest of Spain temperature has risen by around +0.5 °C.

The net influence of evaporation in global mean climate has been assessed by Ban-Weiss [111] and coworkers, who perform a highly idealized set of climate model simulations and showed that altering the partitioning of surface latent and sensible heat by adding a 1 W m^{-2} source of surface latent heat flux and a 1 W m^{-2} sink of sensible heat (i.e. decreasing the Bowen ratio) leads to statistically significant changes in global mean climate. This study suggests that for every 1 W m^{-2} that is transferred from sensible to latent heating, on average, as part of the fast response involving low cloud cover, there is approximately a 0.5 W m^{-2} change in the top-of-atmosphere energy balance (positive upward), driving a decrease in global mean surface air temperature of 0.54 K. This occurs largely as a consequence of planetary albedo increases associated with an increase in low elevation cloudiness caused by increased evaporation. Thus, their model results indicate that, on average, when latent heating replaces sensible heating, global, and not merely local, surface temperatures decrease. Ban-Weiss's “latent heat source simulation” consisting to increase the upward latent heat flux from the land surface to the atmosphere by 1 W m^{-2} resulted at the top of atmosphere in an increase in net shortwave radiation of 0.2±0.1 W m^{-2} (upward positive), and an increase in upward longwave radiation of 0.80±0.06 W m^{-2}. Ban-Weiss concluded

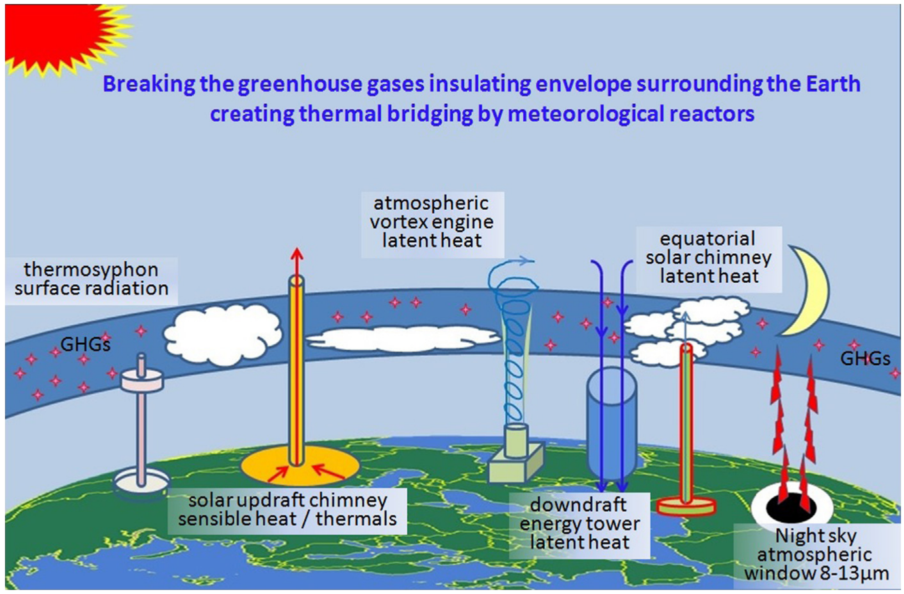


Fig. 11. Principal longwave radiation targets of meteorological reactors.

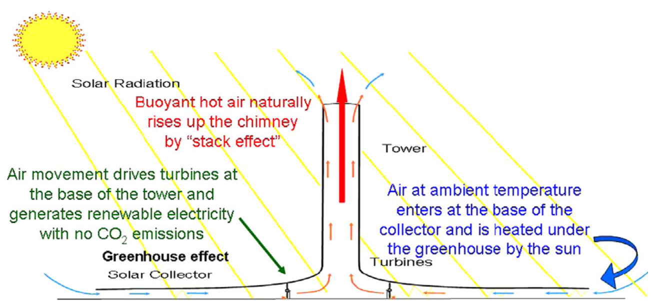


Fig. 12. Working principle of a solar updraft chimney [121] the air buoyancy is due to the temperature differential, which implies density differences under the greenhouse cover, thus a pressure difference and an updraft.

that his study points to the need for improved understanding between changes at the Earth's surface, and how they interact with fluxes at the top of the atmosphere to drive regional and global climate change.

5. ERM to produce thermal bridging

The GHG effect occurs in the longwave range and is mainly caused by the increase of CO_2 concentrations. CCS and CDR address the cause of the GHG effect and if the CO_2 concentration decreases, then the outgoing longwave radiation to the space increases.

SRM reduces the amount of energy reaching the Earth surface, addressing the incoming shortwave radiation by strategies and techniques producing a "parasol effect". But compensating longwave radiation problems by shortwave radiation management, even if able to compensate on average for the same amount of temperature increase, is not equivalent and might for instance in more rain in some parts of the Earth, and droughts [112] in others.

We propose ERM that addresses the longwave radiation portion of the spectra represented in Fig. 10. The goal is to increase by different ERM techniques, both sensible and latent heat transfer out to space, and also radiation through the atmospheric window, the thermals, and all global surface longwave radiation.

As GHGs are good insulating "materials", we propose to create thermal bridging in the GHG envelope surrounding the Earth with gaps or breaks in this GHG insulating envelope in order to create pathways for heat loss that bypass the thermal insulation that causes global warming. These atmospheric thermal bridges are thermals and warm updrafts or cold downdrafts. Several devices called meteorological reactors are proposed, that can provide an uninterrupted "short circuit" between the surface level and the top of the troposphere, and then the outer space.

The atmospheric thermal bridges provided by these devices will result in a bypass with an accelerated heat loss from surface to the space through the thermal insulation caused by the GHGs. The MR proposed are power-generating systems that are able to transfer heat [113] from the Earth surface to the upper layers of the troposphere.

For instance, it is known that thunderstorms influence the climate system by the redistribution of heat, moisture and momentum in the atmosphere. The effects of convective updrafts from various types of clouds have been explored by Masunaga [114] and Folkins [115]. On short timescales, the effect of deep convection on the tropical atmosphere is to heat the upper troposphere and to cool the lower troposphere by moisture transport from the atmospheric boundary layer to the free troposphere. Cold rain and an atmospheric boundary layer cooling is linked with the atmospheric response comprising a lower-tropospheric cooling and upper-tropospheric warming, leading to a momentary decrease in temperature lapse rate.

Jenkins [116] as shown that especially in the case of mineral dust, the aerosols can also act as effective ice nuclei, enhancing the freezing of cloud droplets and thus increasing cloud updrafts and cold-rain precipitation.

From previously described computer simulations made by Hansen [106] and Ban-Weiss [111] and from real life global scale observations, it can be anticipated that a method or a strategy that will allow a power plant or an industry to transfer a considerable amount of their waste heat (dry or humid) at high altitude instead of rejecting it at the surface will somehow participate to cool the hearth. If numerous wind turbines can do it by acting on horizontal winds [105], probably that vertical drafts also. Unfortunately current dry or wet cooling towers used by the power industry do not fulfill these criteria. If a method or strategy that rejects heat in altitude is CO_2-free, cheap and at the same time allows production of renewable energy the benefit could be important, not only for the climate but also for human and other

living beings. Fig. 10 represents the different longwave radiation origins that are the target of ERM and Fig. 11 the principal unusual renewable energies that are proposed to reach this goal.

6. Transferring surface hot air several kilometers higher in the troposphere

6.1. Solar updraft Chimneys: power plants that run on artificial hot air

A solar tower [117,78], also called a solar aero-electric power plant, is like an inverted vertical funnel. The air, collected at the bottom of the tower, is warmed up by the sun, rises up and drives a turbine which produces electricity [118] (Fig. 12). Indeed, the thermal radiation from sunlight heats the air beneath a glass or plastic cover, the hot air rises up a tall chimney which causes a decrease in pressure. Thus, cold air is sucked by the rising hot air within the chimney, which creates surface wind inside the GH. At the bottom of the chimney there are several turbines [119] that catch the artificial wind coming into the chimney. The turbines generate electricity. Thermal energy storage [120] under the collector allows peak load and night production. The promoters of this technology expect it to be cost-competitive with electricity from the grid, meeting the demand profile and thus being the first non-intermittent renewable energy source to reach a primary provider status. Of course several solutions exist or have been developed for energy storage of other intermittent renewable energies, as thermal storage for CSP (high temperature melted salts in tanks, for 2 or 3 h), chemical batteries or hydrogen production (from water electrolysis) for wind turbines and PV. All these storage systems have for the moment low storage capacity and require high investment costs.

Pumped-storage hydroelectricity is the most established technology for utility-scale electricity storage and has been commercially deployed for decades. The world pumped storage generating capacity is currently about 130 GW. This energy storage method is in the form of potential energy of water. The facilities generally use the height difference between two natural or artificial water reservoirs and just shift the water between reservoirs. Low-cost off-peak electric power from nuclear power plants or excess electricity generation capacity from wind turbines is used to run the pumps and transfer water to the higher reservoir. During peak load or for load balancing water is released back into a lower reservoir through a turbine generating electricity. Reversible turbine/generator assemblies act as pump and turbine.

Compressed air energy storage in underground caverns or in old salt mines is also an energy storage possibility, but few locations exist and storage capacity is lower than for pumped storage hydroelectricity. Also as the compression of air generates heat and the air expansion requires heat (the air is colder after expansion if no extra heat is added) the system is more efficient if the heat generated during compression can be stored and used during expansion, but this increases the investment costs and the complexity of the system.

For the SCPP, which is a low temperature difference thermal power generation system, gravel, water in plastic bags or tubes, and even the soil can be natural energy storage materials. Adding the storage capacity is relatively cheap. Considering the large area of the collector, the SCPP can generate output power continuously and steadily day and night. The use of low temperature solid/liquid phase change materials (PCM) will considerably increase the initial investment of building a commercial scale SCPP.

Quite numerous prototypes have been built in different countries, but only a unique large SCPP prototype was built in the 1980s in Manzanares, Spain by Schlaich [122–124] and produced 50 kW. According to an announcement from the private company EnviroMission at the end of December 2011, the 200 MW La Paz Solar Tower Project in Arizona, USA, should be on line during the first quarter of 2015 [125]. However, the 200 MW figure seemed over estimated, as the same company announced for 2006 a similar power plant in Buronga, Australia, which targets the same power output with a 1.3 times taller chimney and an almost 2 times larger GH, but nevertheless a 30 year power purchase agreement was signed with the Arizona power authority [125].

Another private new competitor appeared [126] which intends to develop 200 MW projects and announced having already purchased a 127,000 ha site surrounding the township of Tuckanarra, in the Mid-West region of Western Australia.

Two years earlier, in December 2009, it was announced that a much smaller 200 kW SCPP demonstration pilot was completed in Jinshawan, Wuhai, Inner Mongolia, China, and that a 25.1 MW SCPP was scheduled for December 2013, the construction being expected to account for 2.510.000 m^2 of desert area and 1.26 billion RMB investment [127] ($200 million).

The effects of water vapor and possible condensation in a large SCPP are an important issue and were investigated by several researchers, particularly by Kröger [128]. Of course, water should not be evaporated under the GH as it will reduce the power output because of the latent heat of vaporization needed, and as a result the air temperature differential will decrease; but if moist air enters inside the GH, it improves the plant driving potential and condensation may occur inside the chimney of the plant under certain conditions, releasing inside it the latent heat of condensation. Pretorius [129] described a plant model that takes into account the effect of water vapor in the air inside and outside the plant, and considers the possible condensation of the air inside the chimney of the plant.

Ninic [130] studied the impact of air humidity on the height potential (the height at which disappears the buoyancy force of the collector air ascending with no solid chimney) and on the increase of the operating potential and efficiency of the whole plant. The height potential could be considerably increased if the air entering the collector is already moistened.

The cloud formation in the plumes of SCPPs was studied by VanReken [131] and the results indicate that for very high water vapor concentrations, cloud would probably form directly inside the chimney; with possible precipitation in some cases. For more moderate water vapor enhancements, the potential for cloud formation varied seasonally and was sensitive to the assumed entrainment rate. In several cases there was cloud formation in the plume after it exited the chimney. The power plant performance can probably slightly be reduced by these clouds, but these low altitude clouds could also have a beneficial effect on GW by albedo modification.

Zhou [132] studied the special climate around a SCPP and then, using a three-dimensional numerical simulation model, investigated the plume of a SCPP in an atmospheric cross flow [133], with several wind speeds and initial humidity hypothesis. It was found by Zhou that relative humidity of the plume is greatly increased, due to the plume jet into the colder surroundings. In addition, a great amount of tiny granules in the plume, originating from the ground or contained in the air sucked, act as effective condensation nuclei for moisture, and condensation would occur. A cloud system and precipitation would be formed around the plume when vapor is supersaturated, with maybe some beneficial effects in the deserts where SCPPs are intended to be built.

Furthermore, the latent heat released from the condensation of supersaturated vapor can help the plume to keep on rising at higher altitudes. Even if it depends on wind conditions [134], the plume often reaches more than 3 km up to 4 km which was the upper limit of the Zhou simulation model (Fig. 13). The numerical

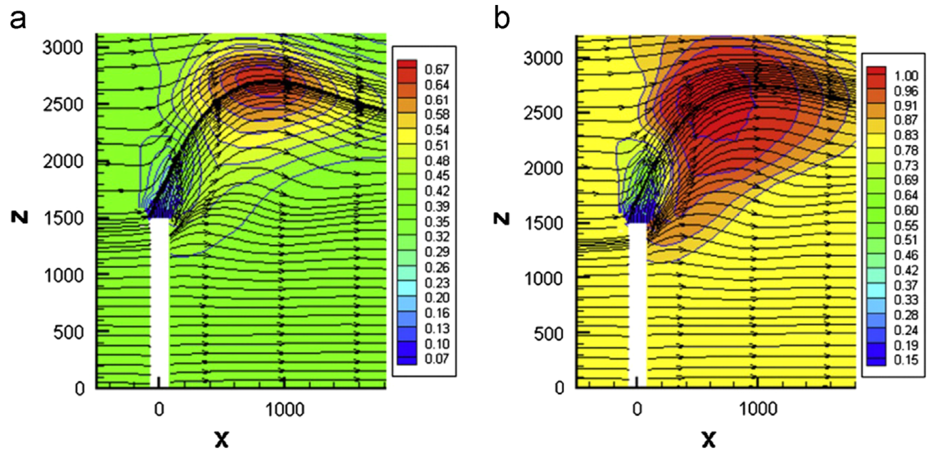


Fig. 13. From Zhou [133] streamlines for atmospheric cross flow with 40% (a) and 80% (b) relative humidity.

model can probably be improved, especially with larger spatial dimensions, but nevertheless this first work on the subject is instructive. Several chimney shapes have been studied [135] but little research as yet been done on implementing a convergent nozzle throat at the top of the tower, increasing output air speed and condensation nuclei concentration by reducing the flux area.

In order to release the air at higher altitudes, the SCPPs can be built in higher locations on Earth, where insolation and average yearly temperature are optimal. In Mexico, the city of Nogales is located at an altitude of nearly 1200 m, and has almost the same temperature and insolation [136] characteristics than La Paz, Arizona, USA, located only at roughly 130 m altitude. So the air of a similar SCPP will already get out 1 km higher. Similar high insolation locations at high altitude can be found elsewhere, for instance in the Atacama Desert.

Zhou [137] described a SCPP with a floating chimney stiffened onto a mountainside and analyzed the power generation potential in China′s Deserts. This type of SCPP is expected to be less expensive taking profit of local mountains, and is suitable for the special topography in China with vast desert belt surrounded by high mountain chains up to thousands of meters. His results show that the possible power obtained from the proposed floating SCPP in the Taklamakan or in the Badain Jaran Deserts can satisfy the total electricity consumption in China, and that the total expected power in the 12 Chinese deserts and sands, reaching more than 25,000 TWh per year, can even supply the electric power needs of the entire world.

Over the course of the 21st century we will probably progressively shift to an electricity-based economy [138], as all the renewable energies (wind, hydro, concentrated solar power, photovoltaic, geothermal, tidal, wave and biomass) and nuclear energy essentially produce electricity. The global electricity output is currently estimated at ~5000 GW. Some scientist like Cherry [139] and Doty [140] proposed that after peak load, the unused capacity of power plants could be diverted to recycle CO_2 and produce high energy content and easy to carry domestic or vehicle synthetic fuels. Thus maybe more than 10,000 GW will be needed for the entire world needs.

As the GH collector of a SCPP is the most expensive constituent (50–70% of total cost), Bonnelle [141,142] imagined several concepts of solar chimneys without collector canopy, for instance tropical ones floating over the hot ocean, and whose working mechanism is based in latent heat of condensation. Hot air saturated by moisture enters the bottom of the chimney, and the driving force that lifts up all the air column is the water condensation several hundred meters before the tower exit: the latent heat released quite high in the tube warms the air inside and the buoyancy produced pumps up the entire air column. Distillated water is a sub-product than can be valued; Authors imagined that lots of these SCPPs could cool the ocean surface, and might prevent or reduce intensity of hurricanes. Hagg [143] developed similar concepts called "hurricane killers".

6.2. Discussion about the cooling effects of kilometric high chimneys and towers

It should be noted that the SCPPs are generally intended to be built in deserts, where albedo is generally high and air is quite dry, whereas the concepts proposed by Bonnelle or Hagg are applied at oceanic locations, where albedo is lower and air is quite humid. The purpose of the SCPP is to produce renewable electricity, but the yield is relatively low, 3% in theory, but only 1–1.5% in practice for a 1 km high tower after subtracting pressure drop and other loses [142]. So at the exit of the chimney, the hot air has still some kinetic and thermal energy. This thermal energy could be radiated back to space and thus help cooling the Earth by outgoing longwave radiation, increasing mostly sensible heat flux, as targeted by SCPPs in deserts, or latent heat flux for Bonnelle′s tropical towers.

At this point the question is: will the heat released by the SCPP at the top of the tower be trapped in the troposphere, or a meaningful amount of it will escape out to space as longwave radiation? The "ghost forcing" simulations made by Hansen [106] give confidence on a positive answer, but at what extent? At ground level the greenhouse of the conventional SCPPs trap almost all the solar radiation that otherwise would have been reflected: thus will the radiation back to space be larger on average?

This evaluation is out of the scope of this review and needs further studies, but maybe a very simplified calculation can be intended here. According to the NASA Earth observatory [144] at an altitude of roughly 5–6 km the concentration of GHGs in the overlying atmosphere is so small that heat can almost radiate freely to space. A simplified calculation can be made at the altitude of 5500 m, which is roughly the point in the atmosphere where half the amount of air is below and half is above [145]. Thus, it can be assumed that if heat is transferred at this altitude, as the infrared radiation will be emitted in all directions, the re-absorption will at least be cut in half (some downward radiation will be reflected). The Sun′s energy electromagnetic radiation output is composed of approximately 9% ultraviolet (UV) rays, 41% visible light, and about 50% IR. At the Earth′s surface the composition of the electromagnetic radiation is on average 3% UV, 52% visible light and 45% IR. Of course the longwave radiation of the hot air gases that are rejected by the SCPPs have not the same

spectral composition than the Sun's radiation. The 50% IR downward radiation of our hypothesis will mainly be in the 7–15 μm region as water absorbs IR in the 7 μm and in the 15 μm region, but reemits at 7, 10 and 15 μm meanwhile CO_2 absorbs in the 15 μm region and reemits also at 7, 10 and 15 μm. Both H_2O and CO_2 reemit in the atmospheric window around 10 μm. Depending on the Earth location, there will be more or less aerosols, dust, humidity, clouds and scattering particles, but on average instead of normal distribution we will have y ~69% of energy gone to space and only ~31% reabsorbed into the atmosphere. In other words, the air which will be either warmed up at 5500 m or transferred already hot at this altitude will lose at least 30% more heat than "normal" air warmed at ground level and submitted to the GH process.

As the polar tropopause is reached at an altitude of nearly 9 km, and the tropical tropopause at 17 km, the altitude of 5500 m might be too conservative as the upper layer of many clouds and dust particles might reflect backwards some radiation going down. As a matter of fact

- man-made aerosols and cloud formation nuclei are mainly located at a lower altitude;
- cirrus clouds (found in 43% of some satellite observations [146]) are semi-transparent in the infrared and their mean effective emissivity is between 0.5 and 0.6;
- in coastal environments, coarse particles are found to account for roughly half of the total scattering and 70% of the backscattering for altitudes up to 1000 m [147].

SCPPs concentrate the heat [148] of a very large area (38 km^2 for a 200 MW model power plant), trapping it under a canopy of glass, instead of letting that heat dissipate into the surrounding countryside or rise to the atmosphere just above. The SCPPs release this heat at a higher altitude (1 km for the Australian project, 1.5 km for the Namibian project) through a chimney of smaller cross-sectional area (13,300 m^2, 130 m diameter,). Thus at the output the thermal column escaping the tower is concentrated more than 50 times (as well as the moisture condensing nuclei naturally present in the air).

The idea of transporting heat upwards through the atmosphere and contributing to lower surface temperature by increasing the flow of upward energy via convection, and then dispersing that heat with the aim to radiate it to space has been proposed by Wylie-Sears [149] and by Pesochinsky [150], but not at the same height. The idea of dissipating energy by high altitude thermal radiation was also suggested by Mochizuki [151a,b]. Both ideas will be exposed later.

Artificial thermals are created by the hot air exiting from the chimneys of the SCPPs. The warmer air expands, becoming less dense than the surrounding air mass. The mass of lighter air rises and, as it does, it cools due to its expansion at high-altitude lower pressures. Colder air is displaced at the top of the thermal, causing a downward or lateral moving exterior flow surrounding the thermal column. The rising parcel, if having enough momentum [152], will continue to rise to the maximum parcel level until it has cooled (by longwave radiation in all directions) to the same temperature as the surrounding air, or until negative buoyancy decelerates the parcel to a stop.

About 89% of the outgoing infrared radiation is affected by the GH effect. The GHGs cause both the absorption and the emission and as the heat must be radiated away, IR fluxes have to be considered. As all gases radiate both up and down, some of the lifted energy by the chimney will be radiated down, with maybe on average little cooling effect, taking into consideration the albedo change made by the solar collector of the SCPP at ground level.

6.3. The two hypotheses for the air released in altitude by SCPPs

First case: if the extra heating is released by the chimney at an insufficient altitude (2–3 km high) it might suppress natural convection to the same extent as the injected extra heat, tending to keep the troposphere with a constant lapse rate and having caused no significant net effect as the atmosphere is often stratified at some ranges of altitudes. If the environmental lapse rate is less than the moist adiabatic lapse rate, the air is stable – rising air will cool faster than the surrounding air losing its buoyancy. Also, a part of the extra heat released can be compensated by the drag produced by the updraft which creates a similar and opposite force to counter that from the buoyancy, thus leading to a temperature increase in the Polar Regions.

Second case: if the extra heating is released by the chimney at a higher altitude (3–5 km), as the lapse rate cannot get any greater than the dry adiabatic rate, local convection will increase the heat. The heat has still to be radiated after that; but the warmer the air or the clouds, the more heat will be radiated from them. Of course radiation will occur in all directions, and thus some of the heat will be radiated down, but the net outgoing longwave radiation to space will still be increased, even if the effect will be partially offset by decreased convection elsewhere after the plume dissipates.

Indeed, the average global cloud height is linked to the average global temperature. Generally, the higher the average cloud height, the higher the average surface temperature, and vice versa [153]. The IR emission by clouds to space represents 26% of the incoming solar radiation, almost the same amount that all the reflected short-wave solar radiation (31%) by clouds, aerosols, dust and the surface. And the lower the average clouds height is, the hotter the clouds are, and thus the more radiation they lose to space, which means the surface stays colder. So SCPPs releasing quite humid hot air can probably be shorter than those releasing relatively low moist hot air (the height potential previously described by Ninic [130]).

It should be noted that SCPPs work on a 24 h/day basis, thanks to thermal storage, there is no intermittency, so the air flux never stops and is quite important: for a 200 MW SCPP with a chimney diameter of 130 m and an air speed of 11.3 m s^{-1} at the turbines, the amount of air that comes out at the top of the tower is of 12.6 km^3 day^{-1}. Although the current objective of SCPPs is to produce electricity and not to accelerate air in order to send it higher in the troposphere, kinetic energy can be given to the air by reducing the tower outlet diameter, thus increasing the air speed and the initial diameter of the thermal column.

To answer the initial question, more numerical simulations are needed using, for instance Kelvin–Helmholtz instability in a spatial way and at a larger scale than used by Zhou [133] to take into account all the parameters, including the altitude of the location where the SCPP will be built, night and day temperatures during the different seasons and different registered wind speeds and humidity levels. Even if in some cases SCPPs do not cool directly the Earth by longwave radiation back to space, at least they provide indirect benefits like avoiding nearly 900,000 t of CO_2 emissions every year for each 200 MW SCPP and this should also be taken into consideration.

Transporting heat upward through the atmosphere and contributing to lower surface temperature was the goal of this chapter.

Further to the previous subsection about waste heat and thermal power plant emissions, it could seem obvious that if all nuclear, thermal and fossil carbon power plants increased significantly the height of their exhaust chimneys (currently only 100–200 m high) in order to their exhaust gases to pass the boundary layer, local cooling could occur not only by heat transfer

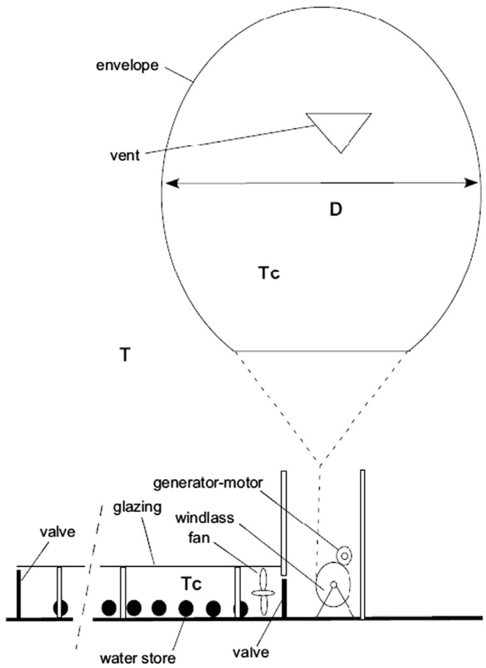


Fig. 14. Elements of the hot air balloon engine as proposed by Edmonds [158] with balloons operating till 10 km in altitude.

but also by plume cloud formation, even if at the global scale no net cooling would result. This idea will be developed later in a further subchapter giving examples of the endless possibilities of use of high towers for global warming reduction. The idea is that for polluting coal power plants, higher chimneys mean sulfate pollution emissions at higher altitude with better dilution and transport and longer tropospheric duration.

6.4. Super chimney

The super-chimney imagined by Pesochinsky [150,154] consists in a huge vertical open duct at both ends, which works as a giant vacuum cleaner, transferring hot air from the sea level to the atmosphere 5 km higher, where temperature is −30 °C. The principle consists in the chimney effect based on the fact that hot air rises by buoyancy above cold air, because hot air is less dense and therefore lighter than cold air. But the process can be made more intense preventing the mixing of warm and cool air, so a chimney prevents inside air from mixing with the outside air until the air exits. The chimney stack effect needs a differential of temperature between the air inside and outside to run correctly. Moreover, the higher the chimney is, the more efficient it is.

It is a similar concept to previously described SCPP [148], except that there is no solar collector at the bottom of the tower, which usually couples the GH effect to the sucking effect of the chimney. According to Pesochinsky the temperature difference between the bottom and the top of the tower is sufficient. Another difference with conventional SCPPs concerns the size, 5–10 times bigger: up to 10 km high with a diameter of up to 1 km. Even if these heights have never been reached by human buildings, some GE / CE projects reported in the initial part of this review envisioned similar heights [59–65].

Furthermore, some authors reported, with such a large duct and in certain atmospheric conditions, that a cold air inflow could occur at the top and as a result a layer of cold air could get out at the bottom of the chimney, the hotter air surface being just pushed up, with the creation of a thermal inversion. In terms of heat transfer the result is nearly the same: cold air down and hot air up.

Indeed, on some Pesochinsky's designs, the tower is alongside a mountain slope or drilled inside a mountain (which seems too expensive) and numerous air pipes are connected on the sides. Di Bella [155] suggested a similar concept by using giant open pit-mines and also recycling waste-heat from power plants. This heat input could be useful to prevent cold inflow entering these large diameter chimneys. To illustrate the potential of these devices, according to Pesochinsky's calculations [156] only 10 super chimneys 5 km high can offset the heat surplus in the Earth atmosphere, which causes current global warming. This would mean that all the atmospheric circulation would be completely reorganized from only 10 points on the Earth's surface: the climate induced perturbations could be much worse than what we want to avoid. Hopefully with smaller, cheaper and more numerous super chimneys, better distributed on the surface of the planet, this deleterious effect can be avoided. The calculations done are rather simple, and were confirmed by Mudde [157] from Delft University of Technology. They are based on a difference of temperature of 50 °C and as the super-chimney will facilitate air convection by bringing masses of warm air up to 5 km, then when the heat from the air radiates out, as it will be already at high altitude, less energy will be reabsorbed by the atmosphere, due to a thinner layer of atmosphere to go through. Therefore, more heat will be leaving the atmosphere, thus reducing the global atmospheric temperature. The authors believe that more scientific studies are needed to prove the concept, and that the technology still fairly mature to build 5 km high chimneys.

Constructional generalities are given by Pesochinsky with no real details: tall skyscrapers already exist; unlike chimneys, buildings entail much heavier construction because there are floors, ceilings, several fluids and lifts going up and down, and all other elements within buildings which are necessary to make it useful for humans. A chimney is just a cylinder, thus is a much lighter structure and can be build a lot taller than any building with new "super-strong" materials, not even described by Pesochinsky.

6.5. The hot air balloon engine to release air in altitude

Edmonds [158a,b] developed the idea of producing electricity by using hot air balloons directly filled by air heated by the sun, by means of a glazed collector (Fig. 14) like in solar chimneys. This system can be summarized as a SCPP where the tall chimney is replaced by a balloon, filled by the hot air produced under the greenhouse. For Edmonds, the lift force of a tethered solar balloon can be used to produce energy by activating a generator during the ascending motion of the balloon. The hot air is then discharged when the balloon reaches a predefined maximum height. Edmonds predicted the performance of engines in the 10 kW–1 MW range. The engine can operate over 5–10 km altitude with thermal efficiencies higher than 5% comparatively to 1–3% for SCPPs.

The engine thermal efficiency compares favorably with the efficiency of other engines, which also utilize the atmospheric temperature gradient but are limited by the much lower altitude than can reach the concrete chimney. The increased efficiency allows the use of smaller areas of glazed collectors than for SCPPs and the preliminary cost estimates suggest lower prices of the kWh produced, as there is a lower building cost.

Then Grena [159] proposed some variants, for instance the use of two balloons bound together (Fig. 15a), the use of warm saturated air from a source such as the cooling tower of a power station or the use of transparent balloons containing inside a black absorber that is directly warmed by the sunlight (Fig. 15b). Grena suggested that the upward drift due to solar energy and the lateral drift due to wind can both be used to generate energy.

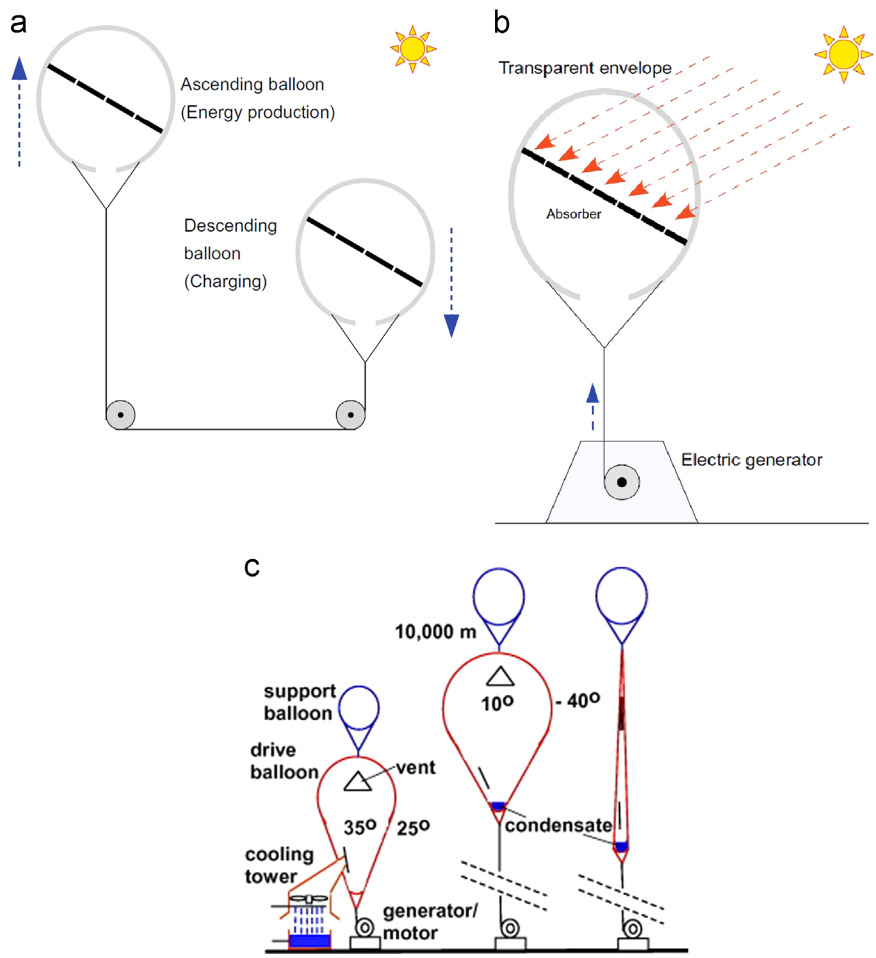


Fig. 15. (a) Double balloon variant of solar balloons proposed by Grena [159]: one balloon ascends meanwhile the second descends and recharges, slowing down the ascent of the first. [158]. (b) Another variant of the solar balloons proposed by Grena: the sun radiation is absorbed by a black collector inside the transparent balloon and heats the air, generating a lift that actions a turbine. (c) Another variant of the solar balloons proposed by Grena: a support balloon filled with Helium is associated with a drive balloon filled with waste heat from power plants, for instance warm and saturated air from a cooling tower. The latent heat of condensation of the humidity allows the balloon to go much higher, up to 10 km. For the descent, the drive balloon is emptied of the hot air at its maximum altitude. The support balloon slows down the descent. The water condensate can be recycled [158]b.

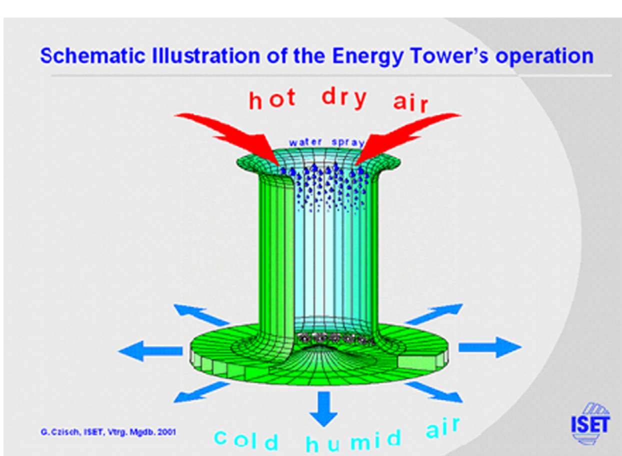


Fig. 16. Schematic illustration of the DET operation reproduced from Czisch [169] and Technion – Israel Institute of Technology.

In a variant, a couple of balloons are used: a big drive balloon filled with hot air and a smaller support balloon filed with helium (Fig. 15c), both connected to an electric generator by a rope. While ascending several kilometers the balloons perform work on the electric generator. At some maximum height of the order of 10 km the larger drive balloon discharges all its hot air into the cold upper atmosphere (thus transferring heat from the Earth surface to the upper layers of the troposphere). Then meanwhile the two balloons are hauled back to ground, the smaller balloon provides support for the empty envelope of the larger balloon. At some height, the latent heat of condensation of water vapor inside the drive balloon maintains the internal air temperature above ambient temperature and provides an increasing lift force with height, plus water. This balloons technology seems quite promising both to produce renewable energy with smaller investment costs than SCPPs, but also to cool the Earth as higher altitudes can be reached by the hot air.

The GE community might also be interested by this hot air balloon concept, as filling similar balloons by the hot flue gases coming out from the exhaust chimneys of polluting coal power plants, can be a very inexpensive way to send sulfates at high altitude, and at the same time produce electricity to compensate for the cost of the installation. The goal can be to install filters on the exhaust of the power plants to remove 95% of the sulfates released in the local environment. Only 5% of the flue gases coming out of the chimney will be used for filling the balloons that will climb 10 km high (or till the stratosphere). In this CE scheme it can be argued that the sulfates sent higher would have been released in the lower troposphere anyway and in an amount 20 times more important. Removing 100% of the SO_x is not

desirable as an immediate warming will result by the elimination of the low altitude reflecting aerosols.

7. Transferring cold air to the Earth surface

7.1. Downdraft evaporative cooling tower for arid regions

The hydro-aero power generation plants, also called downdraft energy towers (DET) [160], were first developed by Carlson [161] from Lockheed Aircrafts, and then by Zaslavsky and Guetta [162–164]. This concept was extensively studied by researchers, was the subject of numerous PhD theses [165,166], and has even been associated to pumped storage and desalinization plants [167].

The DET is a power plant that uses seawater and solar energy accumulated in hot dry desert air to produce electricity. It includes [168] a tall downdraft evaporation tower, water reservoirs, pipes, pumps and turbines (Fig. 16). The DET has to be built inland, in the driest possible location, as the yield is reduced by moisture; but DET should not be too far from the sea, as sea water is needed and pumped by ducts till the DET. Seawater is then pumped till the top of the tower where it is sprayed with numerous nebulizers. The water droplets fall down and evaporate, creating a downdraft cold air flow which is denser than ambient air. The tower is quite large and high (typically 400 m in diameter and 1.4 km high) in order to reach humidity saturation. At the bottom of the tower the heavier artificial wind drives turbines. Only a nearly 1/3 portion of the electricity produced is needed to pump the water to the top of the tower (and from the sea).



Fig. 17. Picture of low altitude clouds over land, modifying the local albedo.

Excess water is used and is not evaporated in order to collect the salt byproduct, also using an electro-coalescence device. In a hot and arid desert, the tower releases at its bottom huge amounts of cold and very humid air that might help to green the desert if some condensation occurs outside during colder nights. If there is a mountainous landscape around, a DET might produce inversion layers. Small altitude inland clouds might form, as sand dust could be good condensing nuclei (Fig. 17), thus increasing in-land albedo.

So this technology might well be the inland counter part of the ocean cloud whitening SRM geoengineering proposal by Salter and Latham [41,43] using Flettner ships. Brackish water is returned to the sea, but geoengineers [170,55] can imagine albedo strategies using this salty water to whiteness controlled and limited areas of desert where there is no groundwater tabs under it.

According to Zaslavsky [171] DET might help cooling the Earth, and actually reverse global warming, as by cooling air in desert regions, the DET could expand the effects of a global natural cooling process called “Hadley Cell Circulation” whereby the Earth cools itself, but occurring mostly only near the equator.

An US private company is developing a similar concept [172] making also profit of the lateral wind (Fig. 18a) to increase downward flow similar to a Japanese wind tower [173] project, and to existing cooling towers that also harness the wind, but at lower altitudes (Fig. 18b).

Multiple air inlets at several heights have also been experimented by Erell and Pearlmutter [174] in downdraft cooling towers. The initial structure (Fig. 18a) proposed by the Arizona “wind clean energy tower” can probably be cheaper to build, as there is less wind pressure outside. This company announced

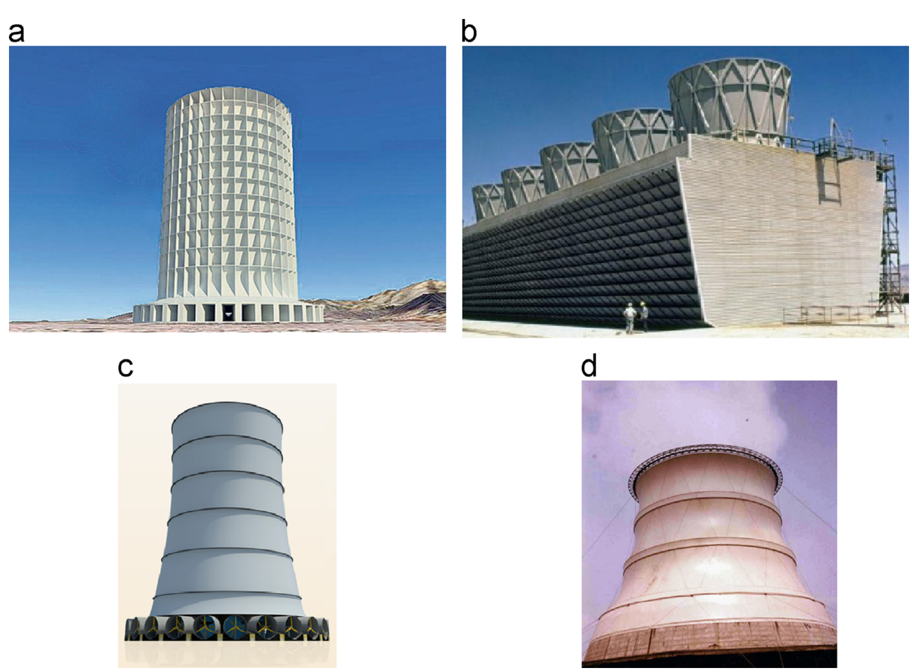


Fig. 18. (a) First energy tower designs from wind clean energy tower [172]. (**b**) Example of existing fan less, cross-flow induced draft cooling tower. (**c**) Current energy tower designs from wind clean energy tower [172] very similar to the ones developed by Zaslavsky [162,164] at the Technion institute (see Fig. 14). (**d**) Textile cooling tower in Bouchain [176], France 1980–1991

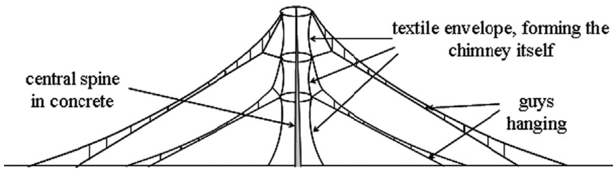


Fig. 19. Light structure proposed for DETs by Bonnelle [142] with the chimney made of textile as pressure inside is higher than outside

recently [175] having selected a site located in San Luis, Arizona, to pursue the construction of their DET facility, but they also come back to a conventional DET type structure (Fig. 18c) similar to the one developed at the Technion institute.

The cooling tower of a 250 MW power plant [176] has been made of a steel skeleton and textile cover made of polyester and PVC coating and with 10 t per meter of tensile strength. This was done in France by the national electricity company EDF after the original cooling tower made of concrete collapsed. After only 6 months of development and construction this refrigerant entered in service in 1980 at the Bouchain site, where it was kept in use for 10 years (Fig. 18d). When deconstructed the plastic sheet was still in perfect condition. The advantages noted by the company were its low cost, the short time of construction and the savings by the faster recovery of the production. If the DET planned in Arizona is made the same way instead of concrete or iron, it can probably be less expensive to build.

In 2003 Bonnelle [142] proposed a DET with a lighter structure (Fig. 19) from the fact that in DETs the pressure inside the duct is higher than ambient pressure, so the walls made of concrete or iron could be replaced by textile ones. Sorensen made a similar proposal with a SCPP, but needed to put the turbines at the top of the chimney as the air pressure inside the tower is lower than outside (Fig. 19).

A comparison has been made of pros and cons of conventional DETs versus SCPPs by Weinrebe [178]: SCPPs appear more profitable, but the potential profits of the lateral winds have not been evaluated.

If the investment costs are much lower, for instance using ETFE foils, and if wind power can also be harnessed at the same time as proposed in the initial design by the Arizona company [172,175], those mixed wind and DETs plants can probably be built closer of the coast, even if the humidity levels are slightly higher. Of course the moister the outside atmosphere, the lower will be the water evaporation so less cold air flow is produced and the power output will be smaller by the evaporative part of the plant. But saving pumping energy (estimated to consume almost 1/3 of total energy produced) and harnessing land breeze and sea breeze can compensate somehow thanks to the wind part of the plant. Thus the brine could be sent directly to the sea, saving initial investment in the tubes and in the electro-coalescence devices. With an investment in a directional output of the cold air towards the sea, these DETs would also be able to produce cloud whitening over the sea (CE SRM technology), with no need of the Flettner boats proposed by Latham and Salter [41,43].

SCPPs and DETs present numerous advantages comparatively to the current wind turbines: their maintenance is easier as the turbines are at ground level; they use artificial hot or cold wind with no intermittency, 24 h/7 days production and, to increase the power, bigger ones can be built with local materials and adding more turbines of the same size, with no need to change the road infrastructure. As a matter of fact, for a single current giant wind turbine of 5-6 MW reached such a big size that transportation is becoming problematic from the manufacture site till their final installation working site.

Wind turbines operate with horizontal winds meanwhile the SCPPs and DETs exploit vertical air currents. Tidal turbines are the underwater equivalent of wind turbines and operate horizontal ocean currents. The perspective is that maybe the equivalent of underwater SCPPs or DETs will be developed to exploit the vertical currents or temperature or salinity differences among the great ocean conveyor belt [179] without disturbing it, and on the contrary with the aim to stabilize the thermohaline circulation [77].

Recently Bauer [180] has developed a one-dimensional low Mach number model applicable to both DETs and SCPPs.

8. Transferring latent (or sensible) heat to the top of the troposphere

8.1. *Creating artificial tornadoes: the atmospheric vortex engine*

The basic source of energy for tropical cyclones is heat transfer from the ocean. According to Renno [181], atmospheric convection is a natural “heat engine”. During one cycle of the convective heat engine, heat is taken from the surface layer (the hot source) and a portion of it is rejected to the free troposphere (the cold sink) from where it is radiated to space. The balance is transformed into mechanical work. Since the heat source is located at higher pressure than the heat sink, the system is capable of doing mechanical work. The mechanical work of tropical cyclones is expended in the maintenance of the convective motions against mechanical dissipation. Ultimately, the energy dissipated by mechanical friction is transformed into heat. Then, a fraction of the dissipated energy is radiated to space while the remaining portion is recycled by the convecting air parcels.

The energy cycle of the mature hurricane has been idealized in 1986 by Emanuel [182] as a Carnot engine that converts heat energy extracted from the ocean to mechanical energy. He derived the Carnot′s theorem from Bernoulli′s equation and the first law of thermodynamics. In the steady state, this mechanical-energy generation balances frictional dissipation, most of which occurs at the air-sea interface. The idealized Carnot cycle as illustrated by Emanuel is in Fig. 20. In the third leg of the Carnot cycle, air descends slowly in the lower stratosphere, retaining a nearly constant temperature while losing heat by electromagnetic radiation to space.

As represented by Emanuel in Fig. 20, in the hurricane Carnot cycle the air begins spiraling in toward the storm center at point acquiring entropy from the ocean surface at fixed temperature Ts. Then it ascends adiabatically from point c, flowing out near the storm top to some large radius denoted symbolically by point o. According to Emanuel the excess entropy is lost by export or by electromagnetic radiation to space between o and o′ at a much lower temperature To. The cycle is closed by integrating along an absolute vortex line between o′ and a.

Michaud [183] proposed several models for heat to work conversion during upward heat convection and completed a model [184] for calculating hurricane intensity. It is clear that real hurricanes are open systems that continually exchange mass with their environment, nonetheless, the Carnot cycle was considered as good enough until Emanuel′s hurricane model has been improved, for instance by Smith [185]. In 2008 Renno [186] proposed a more general theory that includes irreversible processes. A heat engine cannot operate with heat flowing from a single reservoir; the second law of thermodynamics states that it is impossible to achieve 100% efficiency in the conversion of heat into work. Any real heat engine must absorb heat from a warmer reservoir and reject a fraction of it to a colder reservoir while doing work. Renno [186] published a thermodynamically general theory for various convective vortices that are common features of

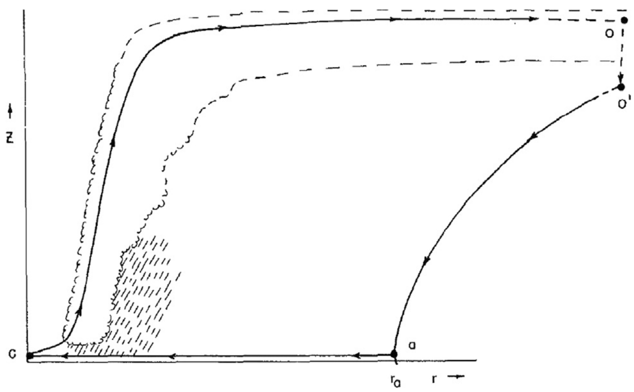


Fig. 20. The idealized Carnot cycle as illustrated by Emanuel [182].

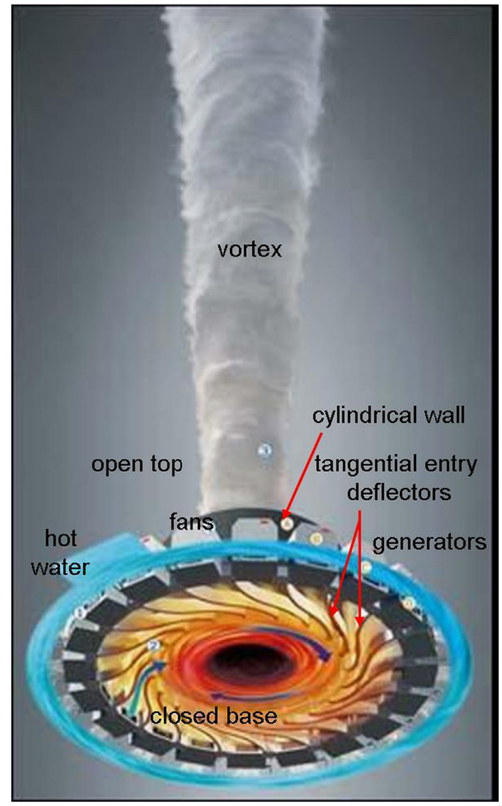


Fig. 21. Atmospheric vortex engine concept from Michaud [195] (illustration by Charles Floyd).

atmospheres: they absorb lower-entropy-energy at higher temperatures and they reject higher-entropy-energy to space, ranging from small to large-scale and playing an important role in the vertical transport of heat and momentum.

Emanuel [187] made estimates of the kinetic energy dissipation of real storms and showed that an average tropical cyclone dissipates approximately 3×10^{12} W. This is equal to the rate of US electrical power consumption of the year 2000; but an exceptionally large and intense storm can dissipate an order of magnitude more power. The thermodynamic disequilibrium that normally exists between the tropical ocean and atmosphere allows convective heat transfer to occur. For Emanuel [188] the increasing GHGs alter the energy balance at the surface of tropical oceans in such a way as to require a greater turbulent enthalpy flux out of the ocean, thereby requiring a greater degree of thermodynamic disequilibrium between the tropical oceans and the atmosphere. In 2001 Emanuel [189] made the supposition that much of the thermohaline circulation is actually driven by global tropical cyclone activity. In 2007 Sriver [190] computations showed that mechanical stirring of the upper layers of the ocean by cyclones may be responsible for an important part of the thermohaline circulation and provided some evidence that cyclone-induced mixing of the upper ocean is a fundamental physical mechanism that may act to stabilize tropical temperatures and cause polar amplification of climate change. If this proves to be the case, then the tropical cyclones are integral to the earth's climate system. D'Asaro [191] found that for hurricane Frances the net upwelling was about 15 m. The heat capacity of the ocean is much higher than that of the atmosphere. The heat provided by cooling a layer of water 1 m thick by 1 °C is sufficient to increase the temperature of the bottom kilometer of the atmosphere by 4 °C which would be a large increase in the heat content of the atmospheric boundary layer. Thus, according to Michaud [192], hurricane sea-cooling is primarily due to cooling from above and not to mixing of cold water from below as stated by Sriver [190] and D'Asaro [191] for whom sea surface cooling is due to ocean vertical mixing and not to air-sea heat fluxes.

Warm seawater is the energy source for hurricanes. Emanuel [193] argued that sea spray could not affect enthalpy transfer because droplets that completely evaporate absorb as much sensible heat as they give off in latent heat. As a matter of fact, without spray the interfacial sea-to-air heat transfer ranges from 100 W m^{-2} in light wind to 1000 W m^{-2} in hurricane force wind. Spray can increase sea-to-air heat transfer by two orders of magnitude and result in heat transfers of up to 100,000 W m^{-2}, similar to the heat transfer per unit area obtained in wet cooling towers [192] (with a thermal capacity of 1000 MW, a diameter of 100 m and a the heat transfer area of 5000 m^2). In hurricanes, drops of spray falling back in the sea can be 2–4 °C colder than the drops leaving the sea, thus transferring a large quantity of heat from sea to air. Michaud's calculations show that if the heat of evaporation is taken from the sensible heat of the remainder of the drop; evaporating approximately 0.3% of a drop is sufficient to reduce its temperature to the wet bulb temperature of the air. The heat required to evaporate hurricane precipitation is roughly equal to the heat removed from the sea indicating that sea cooling is due to heat removal from above and not to the mixing of cold water from below.

Trenberth [194] found that a large hurricane can produce 10 mm h^{-1} of rain over a 300 km diameter area. That gives a mass of rain of nearly 200×10^6 kg s^{-1}; multiplying by the latent heat of vaporization, the heat required to vaporize the water amounts to almost 500 TW, an enormous amount of energy as the world's average electrical energy production is of 2 TW. According to Michaud [192], assuming that the intense heat flux takes place under the 5000 km^2 area of the eyewall that gives an eyewall heat flux of 100,000 W m^{-2}.

Based on the huge amount of mechanical and thermal energies of cyclones, Michaud [195,196] proposed a very original and unusual device for capturing mechanical energy during upward heat-convection in the atmosphere.

Other scientists like Nazare [197], Mamulashvili [198], Coustou [199] or Nizetic [200] also proposed devices for producing an artificial vortex by capturing the energy produced when heat is carried upward by convection in the atmosphere like in hurricanes, tornadoes or dust devils. A man-made vortex reaching miles into the sky would act much like as a very tall chimney, where air density and temperature effects can be harnessed to produce electricity from low-energy content gases, such as those rejected from a cooling tower.

The heat source can be solar energy, warm sea water, warm humid air, or even waste heat rejected in a cooling tower. The

atmospheric vortex engine (AVE) developed by Michaud consists of a cylindrical wall, open at the top and with tangential air entries around the base. Heating the air within the wall using a temporary heat source such as steam starts the vortex. Once the vortex is established, it could be maintained by the natural heat content of warm humid air or by the heat provided by cooling towers. Of course, there is reluctance to attempt to reproduce such destructive phenomenon as a tornado, but according to Michaud, controlled tornadoes, rather than create hazards, could reduce them by relieving instability. Indeed, a small tornado firmly anchored over a strongly built station would not be a hazard and the AVE could increase the power output of a thermal power plant by 30% by converting 20% of its waste heat into work.

Cooling towers are commonly used to transfer waste heat to the lower atmosphere. Michaud's AVE is supposed to increase the efficiency of a thermal power plant by reducing the temperature of the heat sink from $+30\,^{\circ}C$ at the bottom of the atmosphere to $-70\,^{\circ}C$ at the bottom of the stratosphere. The AVE process can provide large quantities of renewable energy, alleviate global warming, providing precipitation as well as energy. Recently Ninic and Nizetic [201a–c] as well as Natarajan [202] studied vortex engines and the technical utilization of convective vortices for carbon-free electricity production.

The Michaud's AVEs have the same thermodynamic basis as the solar chimneys. The physical tube of the solar chimney is replaced by centrifugal force in the vortex and the atmospheric boundary layer acts as the solar collector. The AVE needs neither the collector nor the high chimney. The efficiency of the solar chimney is proportional to its height which is limited by practical considerations, but a vortex can extend much higher than a physical chimney. The cylindrical wall could have a diameter of 200 m and a height of 100 m; the vortex could be 50 m in diameter at its base (Fig. 21) and extend up to the tropopause. According to Michaud, in a vortex, the centripetal force in the rotating column of air replaces the physical chimney and prevents cooler ambient air from entering the rising warm air stream. The rising air in the vortex chimney is continuously replaced by moist or warm air at its bottom. The chimney and the rising air column are essentially the same.

Each AVE is expected to generate 50–500 MW of electrical power. The energy will be produced in turbo-generators located around the periphery of the station (Fig. 21).

The AVEs have the capacity at the same time to transfer heat from the surface till the tropopause (thus cool the Earth) and to produce large quantities of carbon-free energy because the atmosphere is heated from the bottom by solar radiation at the Earth surface and cooled from the top by infrared radiation back to space and this will be the driving force of AVE power plants. According to Michaud, the AVEs could be controlled and even turned off at will. This means that while the vortex may possess great power, it cannot become destructive and therefore is far safer than some CE proposals. The AVE concept has already been tested in small-scale models. The larger of the models was 4 m in diameter. A 34 m high vortex is exhibited at a museum in Germany. The main criticism against the AVE comes from the fact that it still sounds very theoretical and no extraction of energy from the vortex has yet been realized. Also the AVE would only work in very specific conditions designed to prevent the air vortex to leave the AVE as soon as power is drawn off to generate electricity and a pilot plant producing more energy than consuming is still expected. Nevertheless, the feasibility of the concept has been demonstrated theoretically and with small scale models, but not yet in an installation large enough to power turbines. Building a prototype of 8 m is underway and a 16 m is planned [203]. To fully demonstrate the AVE concept, a test a prototype might be built at an existing thermal power plant where a controlled heat source of relatively high temperature will be available. With 20–30% of the capacity of the existing cooling tower, the prototype would be able to accept a fraction of the waste heat from the plant and as a minimum will add valuable cooling capacity and reduce cooled water temperature for the plant without risk to the existing plant operation. Then, once the vortex control will be demonstrated under low-heat and low-airflow conditions, turbines could be added to the air ducts and a complete operational AVE system could be tested.

Recently a system similar to the AVE but using Papageorgiou floating type SCPPs has been proposed [204] to be installed on tropical oceanic barges.

It is worth noted that at a SolarPaces congress a SCPP has been proposed without turbines [205], to be used as dry cooling tower for large scale CSP field. In the context of this review where cooling the Earth surface is the goal, a similar approach can be discussed for AVEs. Even if AVEs where only used to replace cooling towers without any production of electricity, after the initial investment done to build them, a real benefit for the local climate can be expected. The saving on water and pumping can compensate for its cost and the AVE will dissipate at high altitude huge amounts of waste heat for almost free. The cost of an AVE with no turbines can be anticipated as quite small compared to the full cost of a large scale SCPP, which costs of construction and land acquisition have been a stumbling block for groups trying to replicate the Manzanares prototype design on a commercial level.

So even if to date the scientific and technological stage of development of AVE is less advanced than the SCPP and DET, it would take little investment for this technology to be in place quickly. Very rapid progress could be made especially since unlike SCPPs and DETs, AVE prototypes of intermediate size have their interest and can be profitable, whereas gigantism is required for the others. For this interesting tool to start it would suffice of the simple but real commitment of a single industrial of the conventional thermal energy sector, even without the purpose of producing energy.

9. Transferring surface sensible heat to the troposphere

9.1. Heat pipes and thermo-siphons

Heat pipes and thermo-siphons consists generally of a sealed metal shell, usually cylindrical [206a–c], and can transport large quantities of heat even with a very small difference in temperature between the hotter and colder interfaces. The devices are filled with a two-phase fluid, and the heat is removed thanks to evaporating and condensing processes. Inside them, at the hot interface, a fluid turns to vapor. Because of its higher pressure, the vapor generated, moves inside the pipe to the colder end zone, where condensation takes place at the cold interface. In a heat-pipe the liquid is then subjected to a capillary-driven flow, generating passive recirculation back to the hot interface to evaporate again and repeat the cycle. In a thermo-siphon the liquid falls down by gravity [207] back to the hot interface to evaporate again and repeat the cycle. Heat pipes and thermo-siphons differ by size (respectively small and big) and by the way the liquid comes back to the heat source (respectively by capillary action or by gravity). The main advantages of the heat pipes and thermo-siphons are their simplicity, the lack of moving parts, no electric power required, absence of noise and compactness and typically require no maintenance.

Heat pipes can work in all positions, included horizontally, thermo-siphons need to be vertical or inclined with a convenient slope and evaporator is bellow the condenser. For heat pipes, a wick structure exerts a capillary force on the liquid phase of the

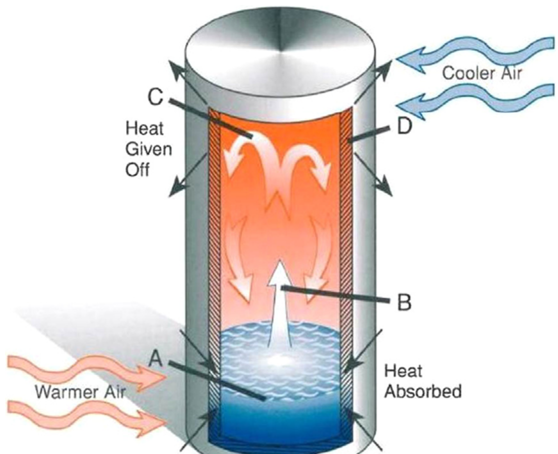


Fig. 22. Working principle of a heat pipe: a thermosyphon [209] (or heat pipe) is a metallic cylinder filled with a refrigerant (liquid+gas). When heat is absorbed at the bottom in the evaporation section A, the filling fluid boils and the vapor raises B. As the vapor reaches the condensing area C at the top of the cylinder, the heat is transferred to the outside environment and the vapor condenses inside. The liquid returns to A by gravity (or in heat pipes by capillarity through a wick D). The cycle can then start again.

working fluid. The wick is generally located on the internal side of the tube′s side-walls and is typically a sintered metal powder or a series of grooves parallel to the tube axis, but it may in principle be any material capable of soaking up the coolant [208]. Quite often both denominations are used indistinctly for any one of the two devices.

Typical heat pipes and thermo-siphons [209] (Fig. 22) consist of sealed hollow tubes made of a thermo-conductive metal such as copper or aluminum and containing a “working fluid” or coolant (such as water, ammonia, alcohol or mercury) with the remainder of the pipe being filled with vapor phase of the working fluid, all other gases being excluded. The materials and coolant chosen depends on the temperature conditions in which the device must operate, with coolants ranging from liquid helium for extremely low temperature applications to mercury for high temperature conditions.

The advantage of heat pipes is their great effectiveness in transferring heat. They are far more effective for heat conduction than an equivalent cross-section of solid copper. Heat flows of more than 230 MW m^{-2} have been recorded at Los Alamos Laboratories [210] for satellite and space flight applications (nearly 4 times the heat flux at the surface of the sun) with lithium inside a molybdenum pipe, which can operate at temperatures approaching 1250 °C. NASA is working with Los Alamos Laboratories to develop heat pipes for use in nuclear reactors to produce propulsion and generate electricity for spacecraft journeying to the solar system′s outer limits.

The use of heat pipes has become extensive over past years for space satellites as they work well in zero gravity environments and also in many electronic devices, such as notebooks and microelectronics. In fact, for computers a remote heat exchanger is often used in order to allow a more compact design.

Other applications of heat pipes are “endless” [211] and include waste heat recovery in industrial boilers, gas–gas exchangers, steam generators, liquid metal heat pipes, high-temperature heat pipe hot air furnaces [212], etc. Heat pipes are also applied to solar heat collection for snow road melting, cooling for CSP power plants [151], cold energy storage for cooling data centers or hospitals, extraction of geothermal heat. Several studies have been conducted to use heat pipes in the nuclear [213,214] industry, for instance to capture nuclear process heat, and transport it to a distant industrial facility producing hydrogen requires a high temperature system of heat exchangers, pumps and/or compressors. The heat transfer system envisioned by Sabharwall [215] is particularly challenging because of very elevated temperatures up to 1300 K, an industrial scale power transport (≥ 50 MW), but also due to a large distance horizontal separation of more than 100 m between the nuclear and industrial plants dictated by safety reasons. As will been seen later, vertical thermosyphons of this size [216] are already operating.

As seen in Fig. 23, thermo-siphons are also used to keep the permafrost frozen preventing the hot oil of the Trans-Alaska pipeline [217] to warm the soil; and also for permafrost preservation under roads and railways like in the Qinghai-Tibetan railway [218]; to prevent seepage in Earth dams by freezing soils in the structure foundations.

It has been suggested to use heat pipes to prevent icebergs and glaciers melting in Arctic ocean [219]. This latter application can counteract this effect of global warming, which acts as a vicious circle as the more polar ice melts, the lower is the albedo of the free water and the more heat is trapped instead of being reflected. A massive deployment of this already existing heat pipes technology can be considered as geoengineering if done in order to help counteract the sword of Damocles hanging over, with the possible melting of permafrost and methane hydrates and the release in the atmosphere of CH_4, a GHG 25 times more potent than CO_2.

9.2. Super power station or mega thermo-siphon

In 1996, the Dutch energy and environment agency Novem examined together with the industry group Hoogovens, a concept invented by the ocean engineer Frank Hoos [220–223]. This project was beyond anything of what had been considered previously in terms of renewable energy power plant. The project called Hoos “Mega Power Tower” (HMPT) was developed to harness the difference in temperature between the warm ocean current of the gulf stream and the icy sub-zero (freezing) temperatures of the atmospheric upper air layers.

In 1992, a thermosyphon with a 37 m long evaporator has been studied [224], but the technological leap was huge.

The smallest version of the huge Hoos tower (Fig. 24) would have been 5 km high, with a diameter of 50 m. The highest and more efficient was set at 7.5 km high. It has to be installed floating on a pontoon at about 30 km from the coast where continuous water currents exist. At the time of the project, a mixture of butane gas and ammonia gas was chosen to circulate inside. This liquid mixture evaporates at the bottom of the giant thermosyphon, thanks to the ocean thermal energy (Gulf Stream), with gas velocities up to 180 km h^{-1} according to Hoos (but in between 20 and 60 km h^{-1} for operation). The top of the tube is frozen between −10 °C and −35 °C, thus liquefying the inner medium. By a central down-comer the condensed liquid falls down back to the heat source at the bottom, evaporates again and falls down again and again. That is at the same time the working principle of the weather machine (evaporating–condensing–raining), but with another fluid and the working principle of thermo-siphons (which generally have no moving parts, on the contrary of the HMPT).

To make profit of the gravity, Hoss planned to install hydroelectric type turbines at the bottom of the central duct in order to generate electricity. The turbines of such a system were supposed to achieve performance up to 7 GW. The structure total weight was estimated to be 400,000 t, and in order to offset its own weight, four ellipsoidal balloons filled with lighter than air gas and with diameter of 360–900 m were proposed to be attached to the tower and sustain it.

Some more recent studies for other technologies can be adapted to this old project. As seen in Fig. 25 for an updraft floating SCPP developed by Papageorgiou [226,227], more balloon

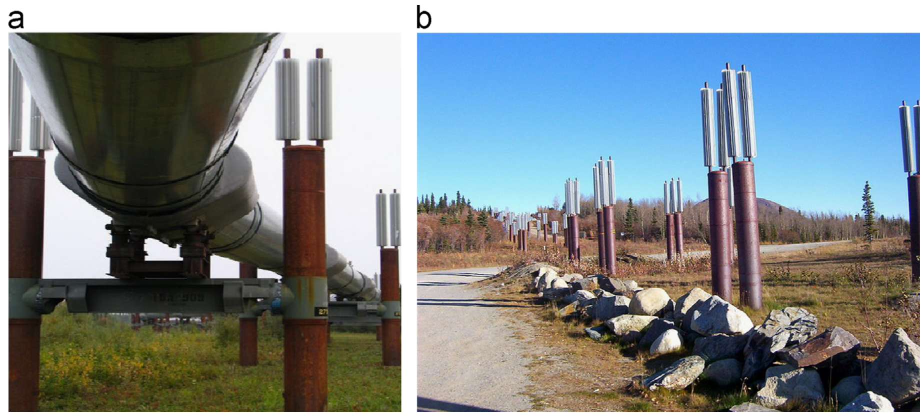


Fig. 23. (a and b) Thermo-siphons on the Trans-Alaska Pipeline [217].

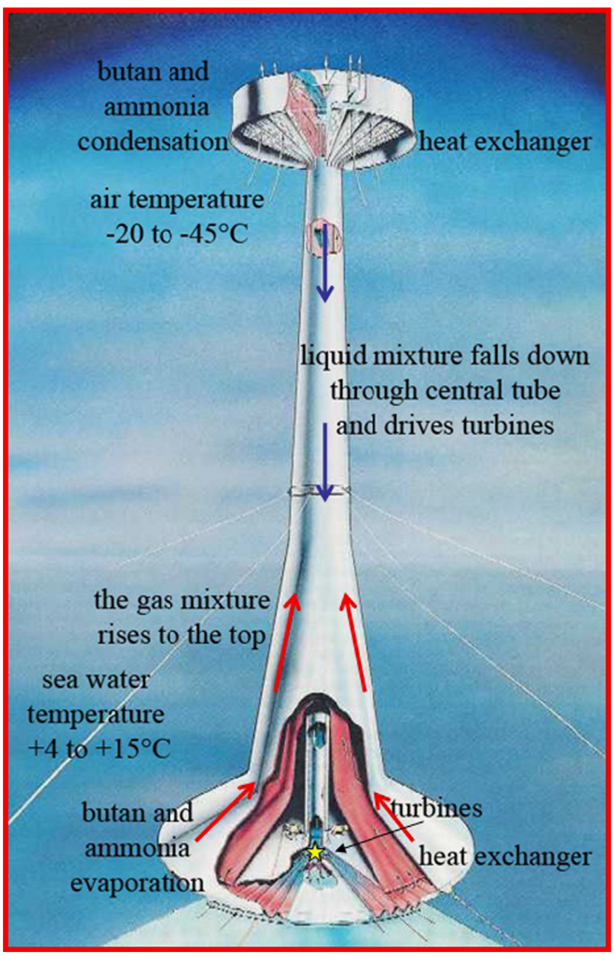


Fig. 24. Representation of the Hoos mega power tower HMPT project [225].

compartments support the own weight of the structure and offer less resistance to lateral winds.

A higher two-tower version has been studied by Hoos who proposed a height of 7.5 km and at the tower top temperatures of −45 °C prevail. In the top of the 2^{d} tower part, hydrogen would have been the circulating fluid, which in turn generates enough lift to be able to support its own weight without the support pillow on the tower shaft. In the lower segment, which would ground with a diameter of 2.5 km, a mixture of ammonia and butane was planned to be used as working medium. The finned heat

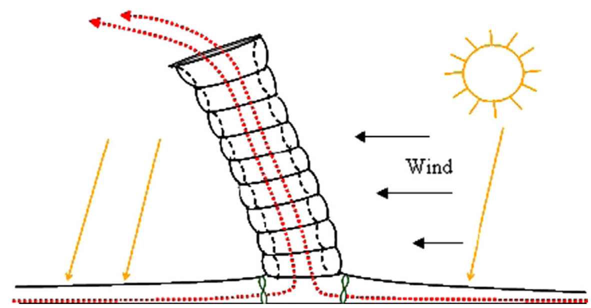


Fig. 25. Papageorgiou's floating solar chimney concept (image from Bonnelle [228]a).

exchanger at the top of the Hoos mega power tower would have a diameter of 1.2 km. The estimated cost was 30 billion dollars.

A feasibility study was conducted during more than 1 year on several technical aspects. It seems that under wind load conditions only small displacements can be traced, due to the enormous weight of the condenser, which functions as a stabilizer for the pipe below, and the floating base on the ocean. At that time therefore, the mechanical structure appeared technically possible, and the project credible for both the company who developed it and for the Netherlands. This 5 km or 7.5 km high HMPTs could seem unrealistic, but geoengineering projects envisions for instance a 15–25 km high hose to spray sulfates, and NASA conducted feasibility studies for "space elevators". The authors believe that more scientific studies are needed to prove the concept, and that it is worth being reevaluated in light of technology evolutions made since the initial proposal by Hoss. Of course public acceptance of such high structures will probably be poor and building technology is not yet mature to build 5–7.5 km high pipes.

Also, due to its big size and power, the system makes it somewhat vulnerable. For example, a fault in the gas flow and half of a European country runs out of power. Better locations with lower wind speed patterns can probably be found.

Since April 2012, a 95 m high thermosyphon filled with a Freon gas is in operation to cool at −40 °C the inner detector of the ATLAS experiment at LHC [216] (CERN – Geneva in Switzerland). Its dimensions are quite modest and small compared to the ones of the Hoos project, but it is worth knowing it. Of course this system has no moving parts and is not intended to produce electricity.

A major problem in 1996 for Hoos was that the functionality of such a system can be hardly reduced to a scale test. But nowadays pilot tests might be possible: progress has been made in scientific

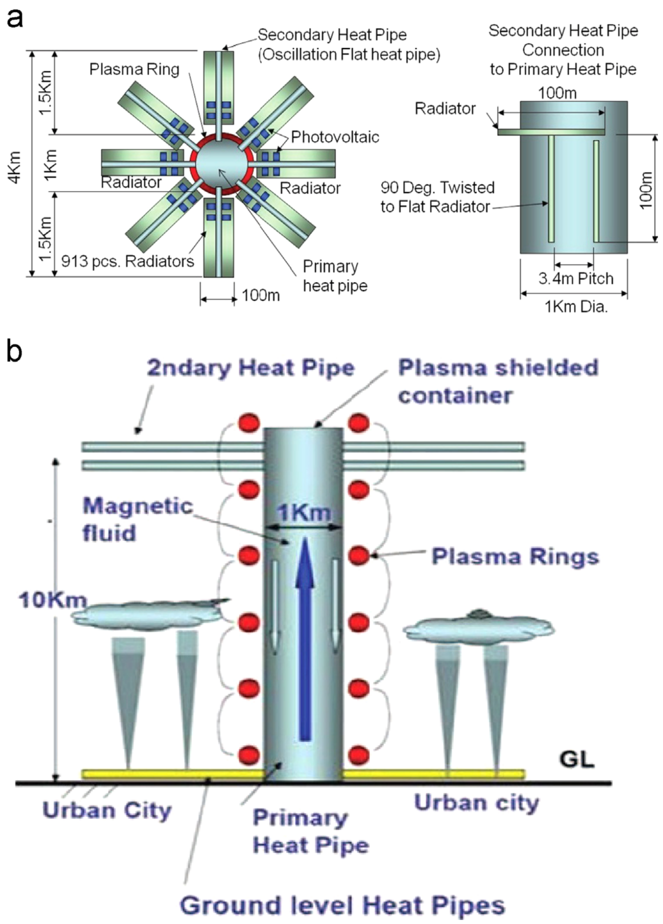


Fig. 26. (a and b) Concept of ultra large scale 10 km high vertical thermo siphon for cooling the Earth by Mochizuki [211]. The upper figure represents the secondary heat pipes placed horizontally at top.

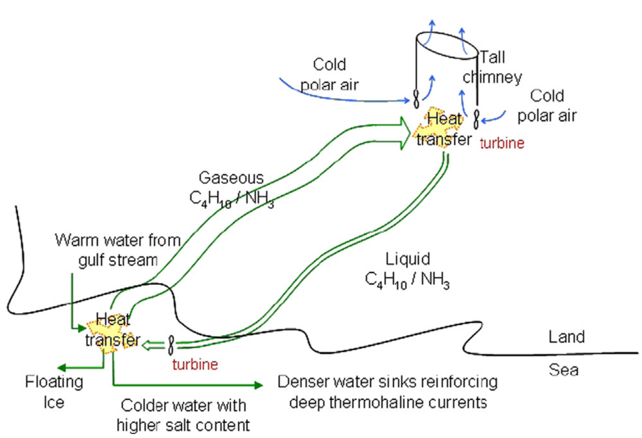


Fig. 27. Bonnelle's 2nd polar chimney concept [228]b.

knowledge on heat pipe and thermo-siphons [229], materials and technologies as well as in all the other engineering aspects of this ambitious project. For instance in membranes, shells [230] and fiber textiles for the lifting balloons, light steel tower, wind load, reduced structural risk. Also heat transfer efficiency of gas mixtures and new gases. Back in 1930, Einstein and Szilard were granted a patent [231] for a refrigerator with no moving parts (no compressor), like a double thermo-siphon, using ammonia–water and ammonia–butane mixtures together.

9.3. Mega thermo-siphon or ultra large scale heat-pipe

Mochizuki and his coworkers developed the concept [151] of giant thermo-siphons (Fig. 26) to help cooling-down the Earth.

The giant heat pipe proposed by Mochizuki [229] is not intended to produce electricity but has an improved design by an additional set of a different kinds of heat pipes at the top of the device that might improve the heat transfer. Preventing ice formation on the outside part of the heat exchanger can be a technical issue.

To evaluate the benefit of using such engines to transfer heat to the upper atmosphere to help offset radiative forcing due to GHGs and global warming can be done in the following way [232]: according to the IPCC and Hansen [233] the radiative forcing due to anthropogenic CO_2 is about 1.7 W m^{-2}. Over the Earth surface of 5.10^{14} m^2 this amounts to 850,000 GW. The maximum of Carnot efficiency of a HMPT engine would be of about 20%. If the efficiency of the device is one half the maximum Carnot efficiency (i.e. about 10%) then in generating all the global electrical output of 5000 GW, the mega power tower engines would transfer about 50,000 GW to the upper atmosphere at an altitude of 7.5 km. Assuming the estimate made by Pesochinsky [150,154] that infra-red re-absorption would be cut in between half and 70%, this heat transfer would correspond to a decrease in radiative forcing of 35,000 GW or about 0.07 W m^{-2}. That would offset only 4% the radiative forcing due to anthropogenic CO_2 present in the atmosphere. But at the same time it will end all CO_2 emissions from fossil fuel electricity production, and their wasted heat released at the surface, as the hypothesis was that these devices provided 100% of our current electricity consumption. So, less than 750 mega power towers can in theory solve the anthropogenic global warming problem. Of course the energy mix of tomorrow will be and has to be as large as possible, with a wide a range of technologies and solutions. In the same manner than for the HMPT concept, the authors believe that more scientific studies are needed to prove the concept, and that building technology for such high structures is not yet mature.

As a conclusion, heat pipe is a known and reliable passive technology that for the moment has been extensively used for heat transfer. For instance, 124,000 heat pipes are used to dissipate heat at the Trans-Alaska Pipeline, mounted on top of the pipeline's vertical supports and keep the permafrost frozen and intact by conducting heat from the supports to the ambient air. Without such pipes, heat picked up by the oil from its underground sources and through friction and turbulence (as the oil moves through the pipeline) would go down the pipelines supports anchored to the ground and would likely melt the permafrost: these 124,000 heat pipes prevent the pipeline to sink.

10. Other energy transfers to the troposphere to cool the earth surface

10.1. Polar chimney

Two similar concepts to the HMPT heat pipe engine have been proposed in 2008 and 2010 by Bonnelle [78,142,228]b as seen in Fig. 27 for the latter and in Fig. 8 for the former. In Polar Regions like in northern Norway or Alaska, where high mountains are close to the sea, this thermal machine has a gas mixture evaporated at the sea level in a first heat exchanger, and conveyed by a large diameter duct leaning against the relief, to the top of a mountain. A high tower sucks polar air by chimney effect and also captures the winds. A second heat exchanger at the bottom of the tower helps the gas mixture to condensate and to return downhill by gravity through a second duct (smaller in diameter), meanwhile warming up the air, that rises inside the chimney. A set of turbines

collect the energy from this buoyant air, and other turbines make profit of the falling liquid. Not only the device can produce renewable electricity, but also helps sea ice formation and cools down the sea which reinforces denser water sink in deep currents.

In Bonnelle's previous concept [142] (Fig. 8), the difference was in the working fluid (water), transported in an open conveyor, cooled at the top of the mountain under a similar chimney, and carried back downhill just before freezing and being released in the open ocean [234]. With this previous configuration, at the tower output moist air is released, which can favor snow falls, and thus increase the polar albedo replacing old ice on glaciers, probably polluted with soot and black carbon by whiter and fresher snow with high albedo. The authors believe that this technology deserves more scientific studies to prove the concept, which is worth being evaluated in light of its capacity to re-ice the Arctic and to prevent methane hydrates destablization.

10.2. Taking advantage of energy potential of the undersea level depressions to install other pipelines and ducts useful to produce electricity and increase local albedo

The concept of helio-hydroelectric power was proposed in 1970 in a progress report on the feasibility of such a plant on the Eastern shore of Saudi Arabia, published by the King Fahd University of Petroleum and Minerals from Saudi Arabia. When topographical and hydrological conditions are favorable to build a dam from the sea or the ocean (an infinite reservoir at a constant level, the source), to a depression well below sea level (the closed reservoir or sink), the evaporation at the "closed reservoir" will tend to decrease its level inducing a flow to move from the infinite reservoir. Therefore the flow of water evaporated by the sun is transformed into a discharge from the "open sea" to the "closed reservoir". Solar energy of evaporation has thus been transformed into hydraulic energy.

In 1972 Bassler [235] proposed the Qattara Depression near El Alamein, only 80 km away from the Mediterranean. The depression is 300 km long and 150 km wide and 135 m deep below sea level at its lowest point. Also in 1972–1973 Kettani and Peixoto [236,237] suggested that the Dawhat Salwah of the Arabian Gulf (Persian Gulf) can be transformed into a large water reservoir, by building a dam from Saudi Arabia to Bahrain, and another from Bahrain to Qatar. Cathcart, Badescu and Schuiling also developed the concept [238,239] and made several other science-fiction like proposals of helio-hydroelectric power plant locations.

In 1980, Assaf proposed a similar concept to this one and to the Zaslavsky's DET, covering a natural canyon [240]. According to Bassler [235], combining with pumped storage, the attainable capacity can reach about 4 GW peak load energy, as in the Qattara Depression region at a level of -60 m the surface area is of 12,000 km^2 and the annual evaporation volume can be of more than 20,000 million m^3 with current evaporation levels of 1800 mm per year. As salt deposits have a higher albedo than surroundings, a global cooling effect can be expected (and no risk for groundwater at proximity).

Hafiez [241] showed that the transformation of Qattara Depression into an isolated anthropogenic inland sea could provide some ocean level adjustment, as well as generate energy, induce rainfall over some of the adjacent desert, reduce hottest desert daytime and coldest night time air temperatures, and permit new local-use fisheries (aquaculture) as well as international tourism resorts. The concept of ocean level adjustment is worth being evaluated in the context of sea level rise by thermal dilatation and melting of continental glaciers.

Thus, these helio-hydroelectric power plants are able at the same time to produce renewable energy, prevent future CO_2 emissions, change local albedo by salt crystallization [54] thus increase global cooling of the Earth, increase latent heat transfer from the ground to the atmosphere and energy transfer back to space, increase evaporation that might help green the deserts and stabilize sand dunes [242], provide useful raw materials for multi-industry use. Last but not least, it can prevent sea level rise, which is one of the principal global warming concerns, thus reducing the 200 million climate refugees expected by 2050 [243,1] to be displaced by climatically induced environmental disasters.

10.3. Examples of the endless possibilities of high towers use for global warming reduction

Although CO_2 is generally considered as well-mixed in the atmosphere, data indicate that its mixing ratios are higher in urban than in background air, resulting in urban CO_2 domes: for example Idso [244] reported measurements showing that in the Phoenix city center, peak CO_2 was 75% higher than in surrounding rural areas and averaging 43% on weekdays and 38% on weekends.

In 2009 Jacobson [245] reported that local CO_2 emissions can increase local O_3 and particulate matter (PM) due to feedbacks to temperatures, atmospheric stability, water vapor, humidity, winds, and precipitation. According to Jacobson, although the pollution health impacts are uncertain, results suggest that reducing local CO_2 may reduce 300–1000 premature air pollution mortalities per year in the U.S. even if CO_2 in adjacent regions is not controlled. Jacobson proposed CO_2 emission controls and regulations on the same grounds that for NO_x, HC, CO, and PM.

London was famous in the 19th century for its smog mainly due to air pollution, and as explained by Asimov [246] the air pollution declined by the construction of higher chimneys that disposed pollution in height in a way that made it fall back to Earth several hundred kilometers away. Of course, the initial problem of poor air quality in London, transformed in a problem of acid rain and sulfur deposits in Scandinavia, may be seen as if the situation had not improved, passing from one problem to another. As with most technological arrangements, the problem has been moved without being resolved. But as noted by Lomborg [247], this argument does not raise the issue of assessing the severity of problems. Highly polluted air in big cities and very dense urban areas kills every year thousands of people, making sick many more and reduces life expectancy. Diluting the pollution and exporting it is not the best solution, but saves lives, reduces illness severity and citizens live longer. When trying to establish the more effective priorities, the self-restoration and remediation ability of our planet has also to be taken into consideration when analyzing the relative importance of problems.

Several engineers like Moreno [248] and Bosschaert [249] have proposed using SCPPs as giant vacuum cleaners for urban atmosphere of highly polluted cities (Fig. 28), thus not necessarily primarily conceived for its energy generating capacity. A tall urban tower could be fitted with particulate and carbon air filters so that the air rushing through the chimney would be cleaned, resulting in urban air quality improvement. The constant air pull of the SUP will partially combat the heat island effect. In hot climates, a shadowing layer with a semi-transparent membrane could be installed to increase albedo, partially blocking out the sun, causing the temperature gradient to drop. A light pressurized inflatable rising conduit as proposed by Sorensen [177] might be easy to install in height between tall skyscrapers (and easy to remove in winter) and will not be too expensive, as the "vacuum cleaner" function does not require turbines and the structure is much lighter than of a conventional SCPP.

PM, black carbon (BC) and soot also are a big health problem, and together with tropospheric ozone contribute to both degraded air quality and global warming. According to Shindell [250] dramatically cutting them with existing technology would save

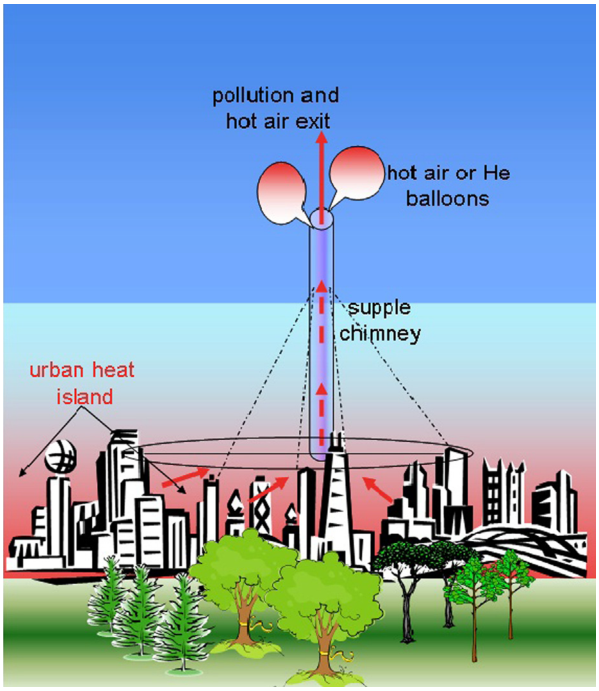


Fig. 28. Using solar updraft chimneys to reduce urban heat island and particulate matter over big cities

between 700,000 and 4.7 million lives each year. Shindell identified 14 measures targeting CH_4 and BC emissions that reduce projected global mean warming of $\sim$0.5 °C by 2050 and avoid 0.7–4.7 million annual premature deaths from outdoor air pollution. He calculated that by 2030, his pollution reduction methods would bring about $6.5 trillion in annual benefits from fewer people dying from air pollution, less global warming and increased annual crop yields production by from 30 to 135 million tons due to ozone reductions in 2030 and beyond. According to Shindell, since soot causes rainfall patterns to shift, reducing it would cut down on droughts in southern Europe and parts of Africa and ease monsoon problems in Asia. Shindell calculated that only in the U.S. his measures could prevent by year 2030 about 14,000 air pollution deaths by year in people older than 30.

As seen in the previous example, tall chimneys can be used as giant vacuum cleaners for dense megalopolis. Taking as a model size the 200 MW SCPP project from EnviroMission, as the air speed is estimated to be 11.3 m s^{-1}, with a diameter of the tower of 130 m, we can calculate that the amount of air pumped by only one SCPP will be 4600 km^3 every year.

If similar devices were associated (for a short period of time) with the most polluting fossil power plants, using waste heat as driving force and equipped with filters for particulates, the air quality will improve considerably. The SCPP efficiency will probably be poor because of pressure drop by dust filters, and less electricity will be produced, but the investment cost will be reduced as no huge greenhouse collector has to be built. Filtration of the exhaust of power plants, cement factories and other dust polluting industries is a well established technology. The pressure drop for particulates will anyway be smaller than for coal and other fossil power plants equipped with CCS, as in this particular case we do not focus on acid gases removal or neutralization, only on solid matter elimination.

As an example, using a general circulation model to investigate the regional climate response to removal of aerosols over the United States, Mickley and Leibensperger [251] found that reducing U.S. aerosol sources to achieve air quality objectives could thus have significant unintended regional warming consequences. They calculated an annual mean surface temperature increase by 0.4–0.6 K in the eastern US, but the temperature rise can be as much as 1–2 K during summer heat waves in the Northeast due to aerosol removal, meanwhile nearly negligible warming occurs outside the US.

Black carbon emissions have steadily risen this last two decades, largely because of increasing emissions from Asia. Soot and BC particles produced by industrial processes and the combustion of diesel and biofuels absorb incoming solar radiation and have a strong warming influence on the atmosphere [252]. On the one side, increasing the amounts of BC and decreasing the amounts of sulfates both encourage warming and temperature increases. On the other side, as several European and North American countries have passed a series of laws that have reduced sulfate emissions by more than 50% over the past three decades, although improving air quality and public health, the result has been less atmospheric cooling from sulfates.

Removing the dust and BC emissions by low cost particulate filters with small pressure drop of the principal Asian coal-fired power plants which account for the higher soot and PM emissions, can help separating the gas (SO_2) from the particles (soot and PM). If at the same time the height of the exhaust chimneys of a part of the main Asian coal-fired power plants which account for the higher sulfates emissions in order to these flue gases (still containing SO_x but no more BC and soot) to pass the boundary layer, not only the pollution will be diluted, but probably it will slightly increase the effective area and atmospheric life-time of the reflecting aerosols, that are normally flushed out of the atmosphere by precipitation. Although atmospheric pollution and aerosols are not well distributed and vary in space and in time [253], the IPCC global estimates of aerosols′ direct cooling effect is -0.5 W m^{-2} and for their indirect cooling effect (by increasing the reflectivity of clouds) is -0.7 W m^{-2}, with an uncertainty range of -1.8 to -0.3 W m^{-2}.

As a matter of fact, a high SCPP-type chimney associated with a coal power plant and equipped with low pressure drop and low cost filters for solids will not only improve the air quality and aid public health, reducing global warming by soot and BC removal, but might be able to preserve the atmospheric cooling from sulfates. The fact is that sulfates in the troposphere have a much shorter resilience time than those in the stratosphere. But taller chimneys can send sulfur gases at a much higher altitude than conventional ones, for a longer period if they pass the boundary layer. Until Asian countries apply similar clean-air regulations than the U.S. and European countries, a progressive transition path can be proposed, for instance one out of five polluting coal power plants is equipped with a higher chimney and the 4 others are equipped with systems to wash out and neutralize the sulfates and NO_x of their exhaust. Whatever the localization of the coal power plants with higher chimneys, the height needed for the exhaust can be calculated in order to obtain a five times longer residence time of the sulfates in the troposphere and an increase of the cooling effects of the corresponding aerosols, even if not as efficient as if they were in the stratosphere as proposed by CE SRM. The major difference is that this proposal uses already ongoing tropospheric pollution and reduces it progressively; meanwhile geoengineering has to inject sulfates intentionally in the stratosphere. Geoengineering proponents can study the effects of these actions, without performing themselves experiments on the stratosphere. One thousand SCPPs could pump at ground level 4 million km^3 of air every year and send it in the troposphere.

The current cost estimates made by EnviroMission are of nearly $0.5 billion each for a 200 MW SCPPs with GH for solar collection (at least for the first prototypes, one could imagine costs going down and overall performances going up). In order to compare, the construction of a coal plant often costs more than 1 billion (3

billion for the last AMP-Ohio coal plant), with an operational life expectancy of 30–40 years, compared to more than 100 years for a solar tower.

Crutzen estimated that the costs to send SO_2 in the stratosphere will be in between $25 and $50 billion every year. With $25 billion, at least 50 conventional SCPPs of 200 MW can be built every year (and four times more if built to use waste heat from power plants, as they do not need a solar collector). Each one of the conventional solar towers will annually prevent over 900,000 t of GHGs from entering the environment: this represents for the 50 SCPPs all together 45 million tons of saved CO_2 emissions per year with only the cost of 1 year of stratospheric sulfate sunshade.

Of course the new 50 solar towers built every year will together generate 50 × 650 GWh per annum (i.e. 32.5 TWh). This is enough to provide electricity to power around 10 new million households every year. The life expectancy of SCPPs is anticipated to be of roughly 100–120 years. For the same $25 billion needed each year for SRM by sulfates, nearly 200 SCPPs associated to conventional power plants can be built, filtering the soot and BC off the air, with an immediate cooling effect (in particular in the Arctic region) and saving thousands of lives.

Synergies between direct CO_2 capture from the air and SCPPs [254] were evaluated and at least a 25% cost reduction of the CDR process arises, with also a simplified scheme for carbon sequestration.

11. Clear sky radiative cooling or targeting the atmospheric window

Matter continuously exchanges energy with its surroundings. Heat transfer can occur by conduction, convection, radiation and also by evaporation combined with convection and condensation at altitude. After sunset when a surface on the earth faces the sky, it loses heat by radiation, but might gain heat from the surrounding air by convection. If the surface is a good emitter of radiation, at night it radiates more heat to the sky than it gains from the air and the net result is that the surface temperature drops to below that of the air. Surfaces can only experience subambient cooling if the thermal radiation given off is larger than that coming in from surrounding surfaces and from the atmosphere. This phenomenon is called night sky radiation cooling. When protected from wind, by clear sky and dry weather, heat transfer from ground surface by IR radiation is much faster than air convection, so a net cooling of the ground can occur resulting in well above air temperatures [255].

In SRM strategies, high-albedo surfaces are proposed to reduce solar heat gains by reflecting an increased amount of solar energy and increasing the albedo. In ERM strategies sky cooling surfaces can pump heat away by radiative cooling to the atmosphere and get rid of the heat directly into outer space. The longwave energy is removed directly by transmission through the atmospheric window. So SRM and ERM are complementary as they can make profit of two distinct types of coolness, the first connected to the whiteness (high albedo) of the surface, which prevents excessive temperatures through reflection of incoming solar radiation, and the second with the coolness that can be captured under a clear sky making use of the atmospheric window, which allows to lose longwave radiation of energy directly into outer space.

The radiational cooling of selective surfaces has been studied by many authors [256–259] since the 1970s, in order to match the atmospheric window (8–13 μm) for more effective cooling by exposition to the clear sky. As seen in Fig. 7, the outgoing longwave radiation through the atmospheric window represents 12% of the total outgoing radiation (17% of the longwave radiation). Space cooling (or nocturnal radiation cooling to the night sky) is



Fig. 29. Average Monthly Sky Temperature Depression (T_{air}–T_{sky} in °C) for July. (Adapted from Ref. [261].)

based on the principle of night heat loss by long-wave radiation in the atmospheric window (8–13 μm). This occurs from a warm surface (the ground or the roof of a building) to another body at a lower temperature (the sky). By clear sky, ground can act as "nocturnal sky radiator" and its cooling by night sky radiation can often reach temperatures 5–10° below ambient (and even much more), so the correlation with the air temperatures measured under a shelter 2 m above the ground are often different. For instance, recent Moderate Resolution Imaging Spectro-radiometer confirmed [260] that at night-time by dry night, the air temperature is often consistently higher than the satellite-measured land surface temperature.

In the 1980s Martin and Berdahl [261] developed an algorithm for calculating the thermal radiant temperature of the sky, based on an empirical and theoretical model of clouds, together with a correlation between clear sky emissivity and the surface dew-point temperature. Hourly sky temperatures have been calculated based on typical meteorological year weather data sets. A typical sky temperature map for the US in July was published by ASHRAE Handbook 2011 based on this work (Fig. 29).

Berger [262] developed an inexpensive apparatus to measure sky temperature. A procedure to calculate the radiative heat exchange between two bodies to be used in the determination of sky temperature, clear sky index or plate emissivity was published by Armenta-Déu [263]. Argiriou [264] showed that more than 90% of the total sky radiation is emitted by the lowest 5 km of the atmosphere, to which water vapor contributes over 95%. He published the frequency distribution of the sky temperature depression for a list of locations over a given period of time.

Over the years, radiative cooling of buildings has attracted considerable research, mainly focused on evaluating the magnitude of the resource and the variations in cooling potential among different locations. Granqvist [265] was also interested in the design of radiative materials for heating and cooling purposes, in particular surfaces capable of reaching below ambient temperatures by benefiting from the spectral emittance of the clear night sky.

Underlying mechanisms have been described by Martin [266]. Granqvist [267] discovered selectively emitting SiO films and Lushiku and Granqvist [268] studied several selectively infrared emitting gases like ammonia, ethylene, and ethylene oxide. Meanwhile Etzion and Erell [269] studied several low-cost long-wave radiators for passive cooling of buildings.

Tsilingiris [270] tested several polymer layers, poly vinyl fluoride being especially good and Berdahl [271] studied MgO and LiF layers. Practical experiments have been conducted by Eriksson and Granqvist [272,273] on thin films of materials such as silicon oxynitride, alumina, and by Granqvist [274] and Tazawa

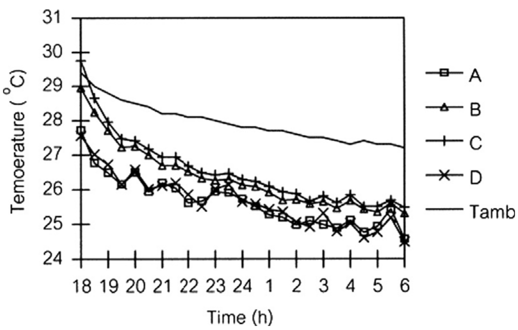


Fig. 30. Hourly variations from 18 h to 06 h of ambient air and different temperatures of 4 different outer surfaces of radiators tested by Khedari [286] (24 January 1998, cloud cover 5%).

[275] on silicon monoxide or silicon nitride [276]. Other alternatives include nanoparticles of SiC and SiO_2, that turn out to be of special interest as proved by Gentle and Smith [277].

Currently, the research areas for space sky cooling focus on alternative cooling systems [278–280] for instance for hot regions where evaporative cooling cannot be used. The aim of these scientists is energy savings compared to mechanical vapor compression systems, by collecting at night cold water [281] in storage tanks to be used in a cooling coil [282] unit during the day, creating a cold storage for the following day. Phase change materials [283] can replace the cold water storage.

One can image improving the daily water production of cheap semi-closed solar stills, as with stored night coolness the condensation yield can be improved. A reverse greenhouse effect was described by Grenier [284] in 1979. Using two water tanks, one for hot storage during the day and one for cold storage during the night, can reduce the temperature differences between day and night in greenhouses for agriculture purposes in hot arid and dry regions of numerous countries. Providing some shadow and with the water recycled inside the greenhouse by night sky condensation might help for a better and more efficient irrigation use, and for the development of a sustainable and self-sufficient food production.

As at night, water freezing can damage PV panels and thermal collectors, research also focused on preventing frost formation and maintaining transparency of a window exposed to the clear sky, for instance using the low-emittance coating SnO_2 on covered glass [285]. Combining heating and cooling in a single surface or single stacked system having suitable spectral properties can be done sequentially with daytime heating and night-time cooling with surfaces designed for sky cooling. The cold sky radiation constitutes a heat sink mainly used for passive cooling systems. Under tropical climates like in Thailand, cooling by night radiation is feasible mainly during the tropical winter season [286] where experimental results showed four different surface temperatures nearly 4 °C below ambient temperature under clear sky (Fig. 30).

Erell [287] reviewed this research work. A cooling effect can also be obtained during the day [257]. Combining in one surface high solar reflection and efficient sky cooling can lead to daytime cooling. As demonstrated by Nilsson [288] and Addeo [289] meanwhile solar reflection keeps the building cool, sky cooling contributes to make its radiative output surpass the solar heat gain so that subambient cooling starts earlier in the afternoon than would be the case without sky cooling. So through some special arrangements it is also possible to achieve useful sky cooling in the daytime and high levels of cooling can be achieved with surfaces of this type as long as there is no incident solar energy and the air convection exchanges are poor.

Among convection covers for radiative cooling radiators, there is polyethylene and zinc sulfide [290] which is mechanically stronger and more resistant to solar UV. They are used as window material associated with selective radiator materials.

Since 2005 the U.S. Department of Energy as conducted extensive research on theoretical [291a] and experimental [291b] evaluation of the "*NightCool*", nocturnal radiation cooling concept and performed performance assessment in scale tests buildings.

Recently Smith [292] succeeded in amplifying radiative cooling by combinations of aperture geometry and spectral emittance profiles and Gentle [293] applied to cool roofs and sky cooling a polymeric mesh which is a durable infra-red transparent convection shield.

A very complete and extensively review of the night sky research and potentials in many areas has been published in 2010 by Grandqvist and Smith [294]. They also described many possible applications of sky cooling to save energy, increase efficiency and prevent new CO_2 emissions.

Together with reverse osmosis, a commonly used method for desalination of sea water is multi stage flash distillation, but both processes are energy intensive methods. Water condensation, occurs when surface temperature falls below the dew point. Several authors [295] have studied dew water recovery using radiative cooling to condense atmospheric vapor [296] on surfaces which can pump heat at subambient temperatures. The technique is referred to as "dew-rain" and typically uses pigmented foils like a unit depicted in France [297] which was able to produce significant amounts of water. A polyethylene foil containing a ZnS pigment helped to collect dew [298] at night in Tanzania and in India [299a] dew collection is being implemented for drinking water. In proper climatic conditions even simple galvanized iron roofs are capable of collecting some dew [299b]. The emitter surface being the coldest, condensation happens first on it and may sometimes occur as dew on the cover as well. But as water has high thermal emittance and is hence strongly IR absorbing, it is essential to remove it from the cover. Of course the low amounts of dew water collected with current clear sky cooling systems cannot compete with the worldwide desalination capacity of 78 million m^3 per day (consuming more than 80 TWh of energy per year) [300]. More than 1 billion people lack access to clean water supplies and an extensive use of desalination will be required to meet the needs of the growing world population. Energy costs are the principal barrier and as for instance by 2030 the total electricity demand for desalination in the MENA region is expected to rise [301] to some 122 TWh. Synergies with sky cooling for increasing process efficiency improved with overnight-generated coolness and complementarities for water collection in remote areas far from the sea or in altitude are worth envisioned.

In order to trap additional power from waste heat from conventional power stations and industries, Grandqvist and Smith [294] suggest that overnight-generated coolness can add significantly to the power output of turbines working at low temperatures. Any low temperature thermal power system can benefit significantly in efficiency by having the cold sink temperature fall by 10–15°. Collecting coolness via sky cooling for an engine condensation cycle with sufficiently cheap and simple materials can also boost up the efficiency of the output from renewable power thermal systems. Grandqvist and Smith also propose that, as large-scale photovoltaic generation systems are commonly located in near-perfect locations for night sky cooling under clear skies and in dry air, they can benefit during the day from night collected cooling in fluids, which may be able to decrease the daily temperatures of the solar cells by 5 °C and thus increase the photovoltaic efficiency [302] as shown in Fig. 31.

One of the major problems of concentrated solar power and related concentrated thermal electricity technologies installed in hot deserts is their need of water as a cold sink, as in arid deserts the water resource is scarce and the use of non-renewable

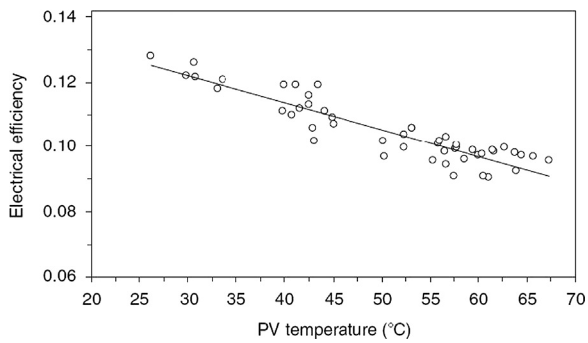


Fig. 31. decrease of electrical efficiency as a function of PV temperature increase reproduced from Tonui [302].

groundwater goes against sustainable development. Although the area needed for this purpose is important, the possibility of storing night sky coolness in phase change products can considerably reduce the daily water needs for cooling. A similar approach was proposed by Bonnelle [205] with SCPPs for CSP dry cooling. Other water use of the CSP or PV industry in deserts comes from the need to remove sand dust from the mirrors or panels: maybe night sky dew condensation can wash out these particles by natural gravity in the early morning.

Electrically powered compressors for cooling systems dump outside the buildings into the close local environment an amount of heat that is larger than the heat removed from the inside rooms. Often, for absorption cycle cooling the coefficient of performance has a value of one and up to three for high performance chillers. That means that between twice and four times the heat that is pumped away is released outside, contributing to the urban heat island of large agglomerations.

In 2003, 395 TWh yr^{-1} were consumed for air conditioning in the world, and by 2030 this consumption is projected to rise by more than three times. Thus around 45 GW of additional external heat load is globally due to air conditioning and, 180 GW is continuously heating up outside urban air. As discussed earlier in Section 3, given typical efficiencies of thermal power plants, their total atmospheric heat load is now probably around 35,000 TWh each year, or at any one time around 4 TW of heat. That is one of the reason why Grandqvist and Smith [294] suggest that it is very important to make more use of solar reflectance and sky cooling, as the more heat derived from cooling will be pumped into the outer space the better. They encourage greater use of night cooling with conventional compressors plus storage as able to send much of the exhaust heat into the outer space instead of into the nearby air.

They also note that when the cooling for buildings is obtained by water evaporation, there is a higher demand on water resources and an elevation of local humidity, both of which are undesirable. In contrast, sky cooling avoids this, and has no adverse impacts on the local environment. On the contrary, sky cooling actually helps ameliorate the urban heat island effect, whereas electrically powered cooling systems and other options will exacerbate it. Sky cooling devices may also be applicable in homes for collecting and storing cold fluid overnight to supply part of the cooling needs of the next day. As shown by Akbari [45], reducing the heat island effect by high albedo roofs can not only reduce the need for air conditioning and lead to energy savings, but also improve air quality and thus have health benefits. Reducing urban smog and ozone [303] will also contribute to healthier cities. By reducing air conditioning needs, the cool-roofs and sky cooling strategies can reduce leakage of greenhouse refrigerant gases that are often worse GHGs than CO_2.

The cool roofs ideas [45,94] have conducted to the development of high reflectivity plus high emissivity tiles or coatings. As most of the NIR solar energy lies at $0.7 < \lambda < 1.2\ \mu m$, it is important that the reflectance is high in this range. The SRM strategy targeting surface albedo [48] can be completed by high thermal emittance materials to also benefit of sky cooling when possible, with adequate covers to prevent thermal conductance. But whitish-looking surfaces are not necessarily very good solar reflectors and may absorb as much as half of the incident solar energy getting warm and leading to a significant internal heat transfer by conduction. It is easily realized that in hot climates roofs should have high solar reflectance combined with high thermal emittance. As recalled by Grandqvist and Smith, the high emittance not only helps to keep down daytime temperatures on roofs and walls but also at night it allows the roof and often the interior and building mass, to cool to a temperature a few degrees below that of the ambient. Among others, they suggest the use of aluminum flakes that have been precoated with nano-thin SiO_2 layers via sol-gel coating before an iron oxide layer is applied. The clear top overcoat imparts a high emittance to this two-layer coating that might be affordable as it is produced by making use of two of the earth′s most abundant oxides. Sheet glass in which the iron content is almost zero is also suggested as possible material that has very small solar absorption and very large radiation output. They also recommend to have a convection-suppressing shield that reflects or back scatters solar radiation while it transmits in the thermal infrared, for instance with microparticles of ZnS, another option being nanosized TiO_2 incorporated in polyethylene [304].

In the purpose of increasing natural convection at a much larger scale, whenever it can be advantageous, for instance to increase valley breeze, mountain breeze, sea breeze or land breeze, the concepts previously described in this section can probably be extended. A strategy could consist in trying to favor, during the summer nights, the amount of cold air coming down from the mountains along the slopes to the valleys, in order to keep cities colder during the day and thus reduce the use of air conditioning and decrease the CO_2 emissions.

Wind is simply air in motion, caused by the uneven heating of the earth by the sun. Solar heating varies with time and with the reflectance and the emittance of the surface. Differences in temperature create differences in pressure. When two surfaces are heated unequally, they heat the overlying air unevenly. The warmer air expands and becomes lighter or less dense than the cool air. The denser, cool air is drawn to the ground by its greater gravitational force lifting, thus forcing the warm air upward. The rising air spreads and cools, eventually descending to complete the convective circulation (Fig. 32a and b). As long as the uneven heating persists, convection maintains a continuous convective current.

Based on the heat island effect on rain described early in this paper [81,82], an international team built up the idea of working with a black material (low reflectivity, low emittance) absorbs energy from the sun and then radiates it back into the atmosphere at night. The air above the black surface could be raised by 40–50 °C above the surrounding temperature, creating a "chimney" of rising air currents.

According to Bering [305], covering nearly 10 km^2 with an appropriate material can make it rain downwind. As it is done near a humid sea coast, clouds will form in the afternoon along a strip as wide as the black surface, and then go up several kilometers. The artificial thermal will boost water vapor to around 3 km where it can condense into water droplets that create clouds, and rain will fall in upwind regions as far as 50 km. The technique is to be applied to any subtropical dry region within 150 km of an ocean. The physical feasibility of the technique was ascertained by

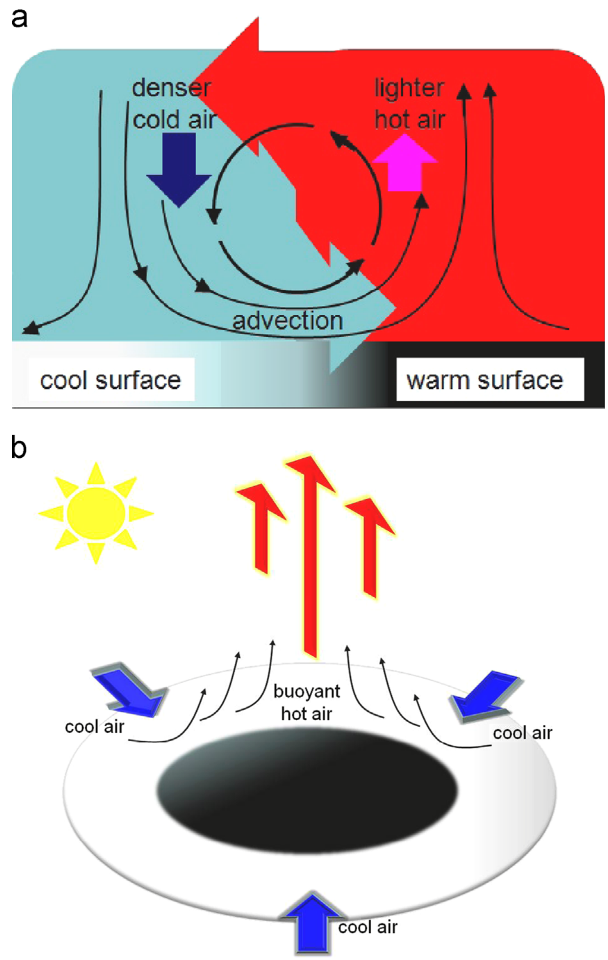


Fig. 32. (a) The convection process. (**b**) The generation of artificial vertical currents by albedo and by radiative forcing modification.

computer simulations at a Spanish location in the Mediterranean coast, but the results were not as good as expected. The forest "biotic pump" hypothesis [306] might let think that the association of a first "black" similar area, with a second area covered with a "white" high reflectivity and high emittance material close to a very humid coast like in the Red sea might give better results in case of the presence of cloud condensation nuclei, which is the case in dusty deserts.

Using man made tornados (rotating in the opposite direction) has been proposed [307] to divert or stop natural ones. Maybe large convection surfaces as studied by Bering, associating sky cooling and also numerous small AVEs, can reduce the destructiveness and the number of fatalities of inland tornadoes by reducing the differentials of temperatures and pressures between the upper layers and the surface, by constantly removing energy to the convective system.

As a conclusion, Grandqvist and Smith make the observation that sky cooling to subambient temperatures has only received spasmodic attention over the years. For them, to date the great potentials of sky cooling have not yet been successfully exploited, despite our ready access to it, probably because the field is not widely understood or appreciated. Also few scientists are active in it, and also as, apart some arrangements for water collection, little effort has been made to develop products based on sky cooling. They think that the quite diverse technological scope beyond these applications seems not yet well understood, and this "knowledge gap" has yet to be bridged. For instance practical cooling at a low cost down to 15 °C below the coldest ambient temperature of the night has been demonstrated. Clearly, the field of sky cooling has so far fallen short of its potential by a wide margin, but it has too much to offer to be neglected. The number of possibilities allowed by sky cooling is huge: of course the goal of this paper is to focus on the possibility to increase the outgoing IR radiation to space by the atmospheric window. But sky cooling presents many other possibilities, like improving renewables electricity production in particular of PV; increasing the efficiency of fossil fueled power plants and of any thermal one; reducing water needs and consumption of the power industry; reducing waste heat release in the close environment at the Earth surface; improving the efficiency of air conditioning systems; reducing the heat island effect; reducing the electricity consumption and the CO_2 emissions by reducing building cooling needs (in synergy with cool roofs); improving human health in urban areas by reducing aerosols and smog; allowing water collection from the atmosphere, and an aid to water condensation in distillation, improving drinkable water access in dry or poor countries; and many other potentials.

The numerous synergies of sky cooling with other energy related technologies have not yet fully been explored. For instance, the thermosyphons used to prevent permafrost melt under pipelines or railways in Northern countries work mainly when the ambient air temperatures are lower than underground temperatures, transferring heat from the ground to the air and keeping the permafrost cool. During the summer, as the air temperature is higher than the condensation temperature of the gas inside the thermosyphon, no heat transfer occurs. It might be possible to improve the upper part of the heat pipe, to make if benefit of the clear sky radiative cooling. High reflectance and high emittance coatings on the top of the thermosyphon, some shadow to protect the condenser part from direct sunlight during the day, a shelter to reduce air convection and a larger surface area exposed to the clear sky at night, all might be possible in order to obtain more effective heat pipes throughout the whole year.

12. Overview of the principal ERM techniques proposed

In Table 2 the principal characteristics of the meteorological reactors described in this review are summarized, with their main heat removal targets and advantages and both physical and technical potentials description. The possible carbon credits have not been taken into consideration.

Thinking to the possible climatic benefits (i.e. avoided hurricane costs, avoided CO_2 emissions and improved human health), the economical potential is expected to be wide, but the costs estimates are yet approximate as only little literature and data is available for the moment.

For SCPPs, the principal costs estimates given in Table 2 are extrapolations from the evaluation made in 1995 by Schlaich [117], then in 2007 by Pretorius [308a], in 2009 by Fluri [308b], and finally from the 2013 actualization made by Krätzig [309]. As Krätzig also gives costs estimates for a 750 m high chimney with no collector, these figures were extrapolated for 750 m high DETs and thermosyphons. For Bonnelle's equatorial SCPP and polar SCPP an extrapolation of both sources was made, together with figures given by Papageorgiou [310] for a floating solar chimney. No figures are available for clear sky night cooling.

For AVEs, Michaud [203b] evaluates to $80 million the total cost of a real scale AVE prototype 45 m height and 60 m base diameter. The vortex obtained will probably reach an height of 9000 m with a base diameter of 6 m. The heat source can be waste heat from a 200 MW thermal power plant. Michaud's major objectives are to increase the power output of the existing thermal power plant by 10–20%, reduce the GHG emissions by 10–20% and also to eliminate the need for the cooling tower.

Table 2
Overview of principal ERM strategies and their characteristics.

Type of MR	SCPP in deserts	DET	AVE	Thermo-syphon	Night sky radiation	Tropical SCPP	Polar SCPP
Outgoing radiation target	Sensible heat	Latent heat	Latent heat+sensible heat	Surface radiation	Thermals+sensible heat	Latent heat evaporation	Latent heat crystallization
Possible additional climate benefits[a]	– Rain in deserts – Heat island effect reduction in urban areas	– Low altitude clouds (albedo) – Green the deserts	– Increase planetary albedo	– Maintain thermo-haline circulation – Re-ice the artic – Reduce hurricanes intensity	– Dew water collection – Heat island effect reduction	– Cloud cover increase – Rain in deserts	– High albedo fresh snow at poles – Sea ice cover increase
Research results available	+++	++	+	+++	+++	+-	+–
Small prototypes built	+++	++	+	+++	+	no	no
Renewable energy production	Yes	Yes	Possible	Possible	No but can improve existing power systems	Possible	Possible
Useful without turbines	Yes dry cooling csp	Yes cooling GH for agriculture in hot deserts	Yes replace cooling towers	Yes many industrial uses	Not applicable	Yes water production	Yes to re-ice the arctic+increase polar albedo with fresh snow
Possible synergies for cost reduction [b]	– CO_2 capture – GHG removal – GH agriculture	CO_2 capture	Use waste heat of thermal power plants	Dry cooling	– Cooling PV panels – Cool paints and coatings – With heat pipes	unknown	unknown
Estimated cost for full operational scale	$300–400 million (750 m high)	$100–150 million (750 m high)	$50–100 million or $10–20 million without turbines [203b]	$100–150 million without turbines (750 m high)	small covers, or coatings in numerous locations	floating $200–400 million	$200–300 million on mountain side
Is a rapid implement-tation possible? (a couple of years)	Yes	Yes	– Yes without turbines – No with turbines	– Yes without turbines – No with turbines – Not at high altitude	Yes	No	No
Possible variants, (other than mountain side)	– Many: floating – urban ventilation – etc.	– With wind towers – With ETFE textile shell	Variants [197,199]	Multiple industrial uses: ex. H_2 production by nuclear	Several to increase breezes from sea or land, from valley or, mountain	Variant [143]	Similar to thermo-syphon

[a] Additional to: avoided CO_2 emissions; heat transfer out to space; and renewable energy production.
[b] Except for tropical SCPPs and thermosyphons, it may be advantageous to use the relief to support the chimney by the mountain side, which reduces the cost for building it; part of the duct structure can be in steel covered with textile sheet instead of concrete.

Table 3
Comparison of the principal SRM[a] and ERM techniques (CDR not included)

Parameters	SRM	ERM	Comments
Type of strategy	Parasol effect	Thermal bridge	Global warming is caused by GHGs which keeps the infrared radiation in the lower layers of the atmosphere
Targeted radiation	Shortwave /visible 31%	Longwave/ IR 69%	It is difficult to compensate a longwave positive forcing by a shortwave negative forcing [311]= > in the case of SRM by sulfates, the rain and wind patterns are modified [112], that means more rains or drought in some places with winners and losers. ERM compensates longwave positive forcings by longwave negative forcings
Global climate benefit of cooling 2 °C	Yes	Yes	Both strategies can be constructed to target compensation of 2 °C global warming on average
Indirect profitability	Yes	Yes	Both techniques if they reach their goal of cooling the Earth will prevent some of the consequences of global warming [1]
Direct profitability[b]	No	Yes	Almost all meteorological reactors (MR) can produce electricity at a competitive cost. The SRM techniques have a cost but do not produce something that can immediately be sold[b]
Proportionality of costs and expenses	No	Yes	SRM global cooling needs a large scale implementation and to permanently maintain it during decades. ERM can have immediate local effects and be progressively implemented. Once built, a SCPP can last 100 years (50 years for other MR) with almost no consumables needs
Prevent ocean rise	Long	Rapid	Some ERM techniques can provide more rain over the continents [312], more fresh snow in the Arctic, more sea ice
Improve crops yield	No	Yes	See Shindell [250]
Prevent CO_2 rise, avoid future CO_2 emissions	No	Yes	Opponents to geoengineering fear that it will not encourage governments to reduce CO_2 emissions [40]. The MR proposed in this review produce CO_2-free renewable energy and can replace fossil power plants
Prevent GHG rising	No	Yes	As clean electricity can be produced by MR, they will favor less coal mining and less shale gas production, thus lower methane and soot emissions. The electric cars will replace internal combustion engines thus less NO_x and PM pollution
Avoid other pollutions	No	Yes	SRM might release sulfates in the stratosphere or salts in the oceanic clouds. An ERM strategy described at the end of paragraph X of this paper might allow to progressively reduce currently existing tropospheric pollution (soot and BC+4/5 of sulfates) and still keep the current cooling level of these aerosols
Prevent ocean acidification rising	No	Yes	ERM can avoid future CO_2 emissions and SCPPs can drastically reduce de cost of direct air capture [254]
Hurricane reduction	Not directly	Directly and indirectly	Global cooling can indirectly reduce hurricane intensity. But MR like AVE and tropical SCPP [142] can directly cool the oceanic waters. Maybe sky cooling large convection surfaces (end of chapter X1) associated with numerous small AVEs can prevent in land tornadoes
Improve human health	No	Yes	See Shindell [250]
Improve development	No	Yes	Poor, hot countries can build SCPPs or DETs in desert locations with local labor and local raw materials
Public acceptance	Poor	Anticipated to be good	Producing clean renewable electricity and avoiding future CO_2 emissions can be better accepted than the “business as usual scenario”
Possible Military use of the technology. Destructive capacity or possibility of misuse	High risk	Low risk	The relatively low financial cost of SMR using sulfates, their high efficiency, with the possibility of a rapid and massive deployment can be feared [40]. ERM is not a rapid action: MR construction is slow and quite expensive; individual MRs cannot be big enough to make significant damages and it seems difficult to build several MR in order to harm. Even the AVE are safe in theory because in case a tornado leaves the generator, it loses immediately the energy that gives him birth and thus dies as soon [203]. Supposing that cyclones could be created with AVE, it is impossible to guide or orient them

[a] As in the most abundant scientific and ethical literature on CE talking of SRM deals with the sulfates in the stratosphere strategy (and although SRM includes a wide range of other different strategies), in the following table the comparisons are made to this particular SRM technique.
[b] The possible carbon credits have not been taken into account, but clearly ERM with MR deserves them, on the contrary of SRM.

In Table 3 several parameters of comparison are given between SRM and ERM techniques, in terms and potential benefits for the climate, but also for the humanity.

SRM do not address the problem of ocean acidification and of atmospheric GHGs (CDR and CCS address only one of the GHGs). Sunlight reflecting methods could cause significant environmental harm, like changing weather patterns and reducing rainfall, damaging the ozone layer, reducing the effectiveness of solar renewable energies, as well as causing sudden and dramatic climatic changes if deployment is stopped, either intentionally or unintentionally. Technical, political and ethical uncertainties are numerous.

ERM strategies seem to have fewer drawbacks. ERM is a set of power-generating systems producing renewable energy and able to transfer heat from the Earth surface to upper layers of the atmosphere allowing heat loss into space. But as this review is the first to propose the concept of longwave energy removal methods, a careful evaluation and examination by other scientists is necessary, recommended and highly desirable. This review suggests several enhanced raise manners for latent and sensible heat energy riddance methods to lose longwave radiation directly into outer space, and a peer evaluation of their potential is required before a correct comparison with SMR strategies can be performed.

13. Discussion

Climate change and global warming is an increasing problem and there is serious concern about the international organizations and governments capacity to take good decisions and fight them effectively. Alternative solutions like CDR and SRM are proposed by the geoengineering community.

On page 20 of the 5th IPCC′s summary for policymakers (released September 27, 2013), it is mentioned that “*Methods that aim to deliberately alter the climate system to counter climate change, termed geoengineering, have been proposed. Limited evidence precludes a comprehensive quantitative*

assessment of both Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) and their impact on the climate system.

CDR methods have biogeochemical and technological limitations to their potential on a global scale. There is insufficient knowledge to quantify how much CO2 emissions could be partially offset by CDR on a century timescale.

Modelling indicates that SRM methods, if realizable, have the potential to substantially offset a global temperature rise, but they would also modify the global water cycle, and would not reduce ocean acidification. If SRM were terminated for any reason, there is high confidence that global surface temperatures would rise very rapidly to values consistent with the greenhouse gas forcing.

CDR and SRM methods carry side effects and long-term consequences on a global scale".

Carbon dioxide removal would need centuries before acting, but addresses the real problem as well as ocean acidification and other CO_2 induced problems. SRM could provide rapid cooling, in few months, but would require to be maintained at least for decades and presents serious side-backs. Some SRM strategies are also cheap and could be so efficient that they can become addictive and may result in forgetting the progress needed in reducing our CO_2 and GHGs emissions.

Public acceptance of geoengineering is poor and CE is often presented as Ulysses choices between Scylla and Charybdis, because the most discussed CE option is the stratospheric sulfates one. But soft-GE options with low risk and with good cooling potential, effectiveness and affordability might exist; some CDR strategies seem to answer these criteria and somehow should not be considered as CE.

The goal of this paper is to demonstrate that other ways exist, like Earth thermal radiation management by several complementary techniques that allow more heat to escape to space.

There is an increasing interest in the development of hybrid renewable energy devices for simultaneously harvesting various unusual forms of energy to produce electricity, thus preventing further CO_2 and other GHGs emissions, and also at the same time allowing cooling the Earth by ERM.

No single source, type or form of energy will answer the enormous energy needs of humankind. Fell [313] described numerous strategies for global cooling and Jacobson [314] reviewed the "*solutions to global warming, air pollution, and energy security*". We believe that some of the technologies presented in this review paper are complementary and deserve being included in the energy portfolio mix of the future.

Stabilizing climate will require within the coming decades the development of primary carbon emission-free energy sources and efforts to reduce end-use energy demand. Of course, no single adaptation or mitigation method, no single geoengineering scheme or idea, and no single MR or URE will solve alone by miracle the global warming and climate change problems.

In a 2002 paper in Science entitled "*Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet*", Hoffert [315] and 17 other scientists, after noting that non-primary power technologies that could contribute to climate stabilization have severe deficiencies that limit their ability to stabilize global climate, concluded that a broad range of intensive research and development is urgently needed to produce technological options that can allow both climate stabilization and economic development. ERM with several of the UREs presented in this paper have this potential as they de-carbonize electricity generation, are not intermittent and reduce the mismatch between supply and demand.

Meteorological reactors as large as those described in the paper do not yet exist, and as such, we view this work as a theoretical problem, but with real potential for real world applications in the coming decades. The SRM techniques also imply a long way of research before safe and large global implementation can be envisioned, if ever.

As a brief summary of what authors think that even if the most advanced MR technique is currently those of SCPPs to be built in hot deserts, SCPPs with large collectors will probably be more useful to produce renewable energy than to cool the Earth (but they can also be used for GHGs removal which will be the subject of a different paper, compared to CDR).

The authors believe that although only theoretical work has been done on other technologies, they deserve further development:

- The polar SCPP variant proposed by Bonnelle (Chapter 10, Fig. 27) has a great potential, as not only it can produce a significant amount of the electricity needs of northern Europe, but it can also re-ice the Arctic, and remove the sword of Damocles of a large destablization of methane hydrates with a possible tipping point.
- The night sky cooling materials to send back to the outer space some IR radiation by the atmospheric window are of great interest, as at small scale the technology readiness level is satisfactory and the scalability also seems good.
- The Grena variant with two balloons of the hot air balloon engine proposed by Edmonds (Chapter 6, Figs. 14 and 15a) to release air in altitude, reduces the investment cost of SCPPs because it suppresses the chimney. As a much higher altitude can be reached by the balloons than by a concrete chimney, the heat transfer to the space can be more efficient, if the amounts of hot air transported per day and per device are similar (several km^3). Small scale prototypes can be built and studies can be performed to use waste heat from existing power plants instead of solar energy. Filling the balloons with humid hot air (from tropical seas), can help reaching higher altitudes when water will condense inside, as latent heat will be released and will warm the inner air.
- To produce renewable energy the Michaud′s AVEs will probably still need a long development time. But independently of electricity production, if the AVE can be proven safe and that there is no risk of producing free tornados or free hurricanes, they can probably be rapidly used only for heat transfer from the Earth surface to the top of the atmosphere, the cooling benefits can maybe easily proven. If an AVE system uses the waste heat from power plants as driving force, water will be saved in cooling towers and waste heat will no longer be released in the rivers or in the oceans. In very humid and hot climates, if proven safe the AVEs can help drying the local atmosphere, and transfer huge amounts of energy to the stratosphere, thus cooling the earth.
  The authors′ opinion is that among MR the most effective and practical technologies to fight against climate change can be AVEs (if proven safe) and night sky cooling. In a configuration where they are not designed to produce renewable energy the R&D required to reach an industrial scale as well as the investment costs will be reduced.

Maybe some of the concepts presented in this review, either for climate engineering SRM as for ERM will never be of practical use; some of them can probably be categorized as pure science fiction; some others could seem "naiveties", but nonetheless the fight of global warming and its tremendous disastrous potential consequences deserves this review. The real problem is the climate change and the global warming being caused by ongoing GHG emissions, not to try to solve it by CE, SRM, CDR, or by the ERM

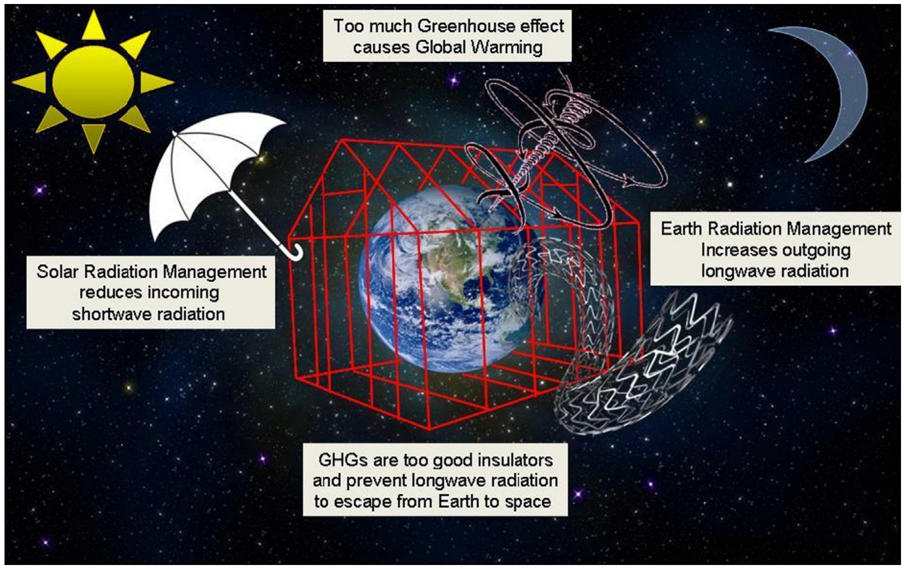


Fig. 33. Creating thermal bridges between the surface and the higher troposphere can help cool down the Earth by ERM by increasing the amount of outgoing IR radiation, meanwhile SRM aims to reduce the incoming shortwave sunlight.

proposals made is this paper. The roadmap for scaling up carbon sequestration from megatons to gigatons [316], or stratospheric sulfates seeding from tons to megatons is not an easy task, and neither is easy the task of convincing investors to build the very first kilometric high DETS and SCPPs that will allow ERM.

The development of renewable energies which are environment-friendly alternatives to fossil fuels use might be completed by new ones which have no anticipated adverse effect on the environment. One of the aims of this review is to give an overview of the state in the art of the numerous ideas and theoretical progress that have been accomplished to date in the development of different MR for energy harvesting. These URE devices can harvest solar, wind and temperature difference energies and allow energy storage or peak production 24 h/7 days. The status and outlook of commercial perspectives is given, in particular for SCPPs and DETs. But, even though significant progress has been made in the research on several of these MR, quite a few have reached the prototype level and SCPPs are the only ones to have been very recently launched at a nearly industrial scale. The industrial potential of these UREs seems important as many of them have the economic potential of provide work to local labor, using local raw materials, and development benefits (electricity and water production in deserts areas). The public and societal acceptance might also be higher than for CE methods.

Coupled with a desire for a miracle that will mitigate energy and environmental concerns, these clean URE are an area ripe for hype. Perhaps several of the technologies described here exhibit good feasibility, yet will never be practical or will not deliver all the promises made, even if they offer high theoretical potential to address the energy challenge. In the future, scientists and engineers will show us among these MR what is possible and also practical. The main idea developed in this review is that GHGs are good insulators of the Earth that prevent normal interactions with the atmosphere (Fig. 33) and keep the earth too hot, so atmospheric thermal bridges have to be created and these UREs can do it.

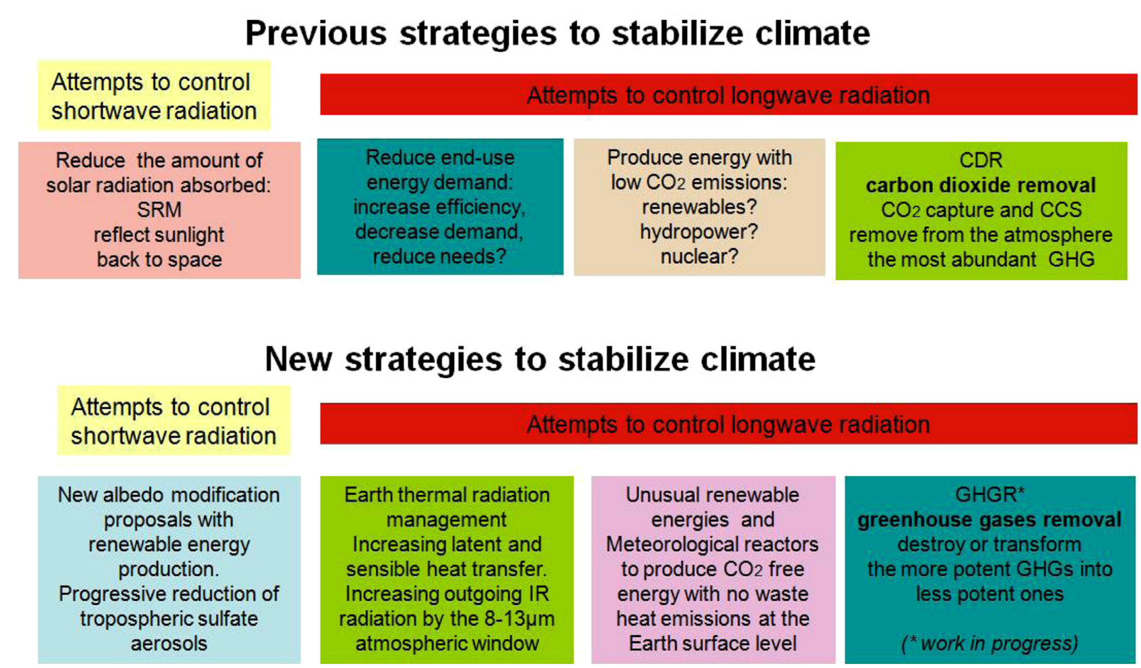
Permafrost melting is considered has an important issue by the scientists who fear leakage or massive emissions of methane, a GHG with a GWP_{100} 25 times higher than for CO_2. Already an enormous amount of thermosyphons are currently used to prevent permafrost melting along pipelines, roads and train-rails over Alaska or Siberia. Large scale use of numerous, more efficient and cheap heat-pipes can help relive the side effects of this global warming induced-problem, as well as for glaciers and for the Arctic melting.

As with the ERM techniques proposed in this article (Table 4), there is no more ocean acidification, acid deposition, ozone depletion, etc., many of Robock's [40] "*20 Reasons why Geoengineering may be a Bad Idea*" are invalid for ERM.

Ocean acidification due to anthropogenic CO_2 emissions is a major problem [318] and current SRM geoengineering schemes do not address it, and on the contrary proposes to add acid rain by sulfate deliberate pollution. The ERM proposed here, as it is able to enhance longwave radiation out to space, and at the same time produce CO_2-free energy, can prevent further CO_2 emissions and help alleviating oceanic CO_2-induced pH change. Even if some meteorological reactors like the AVEs were only used for ERM, not to produce renewable energy, their ability to transfer huge amounts of energy from the surface to high altitude atmospheric layers and then heat to the space would be worth tested rapidly. AVEs are already worth tested because cheaper, scalable, less dangerous or harmful and with more potential benefits than some SRM methods. For instance investing in the development of AVEs with no turbines to produce electricity, and equip all the thermal power plants to replace cooling towers and to disperse the waste heat in altitude will have an initial cost, but then for years it will cool the Earth surface for almost free, and save water.

Many of the UREs discussed in this paper not only could bring limitless clean energy but might also be able to reduce hurricane intensity and their destructive force, reducing insurance costs due to severe weather events, either due to climate change or not. If the $160 billion cost caused by the two hurricanes Katarina and Sandy, plus the $160 billion cost caused by eight other north Atlantic hurricanes of the last decade (Ike, Wilma, Ivan, Irene, Charley, Rita, Frances, and Jeanne) could have been be saved and instead invested in renewable energies and the UREs described here, the benefits for the climate, the Earth and the humanity could have been considerable. The possibility that the destructiveness and the number of causalities caused by the deadly tornado that hit El Reno, Oklahoma on 31 May 2013 could have been reduced by some ERM techniques, should encourage funding research in this area. If not only the UREs can help to equilibrate the energy budget of the Earth, but also avoid health costs and increase economic welfare factors as described by Shindell [250]

Table 4
Old [68] and new strategies proposed to stabilize the climate (* GHGR refers to another paper in progress [317] and is not described here).



that save lives and increase crop yields: these parameters have also to be taken into account.

So far geoengineering has been considered to have direct costs, with indirect benefits for avoiding several of the costs of global warming evaluated by the Stern Review [1]. Several risk assessments have been performed, comparing the different techniques [13] and options. The risk assessment performed by the Royal Society [16], concentrated on their cooling potential, effectiveness and affordability. Meanwhile the MR described in this review have not yet been assessed comparatively to each other, or towards their potential benefits for the climate. Maybe only two of them (SCPPs and DETs) have been assessed by some investors in terms of direct profitability and possible direct financial benefits. The ERM options described here deserve further risk assessment and potential climate and health benefits analysis. The main point is that these UREs can produce CO_2-free renewable energy and be competitive with other existing energies, so allow investors to make profits and at the same time avoid future CO_2 emissions and cool the Earth for free. Meanwhile sending sulfates in the stratosphere has a cost of several billions per year, that will not stop growing and SRM must be continued for decades or even perhaps for more than a century, without reducing the accumulation of CO_2 in the atmosphere, nor solving the problem of ocean acidification.

Grandqvist and Smith [294] think that it is not unreasonable to imagine a world where clean power sources, using some combination of solar energy and sky cooling, become the backbone of a low-carbon economy. The prospect then is not only less pollution but, in due course, lower power cost. Also, as the proceeding global warming will lead to increasing demands on cooling that will soon escalate into a dominant problem for power supply and for the environment, they find fortunate that there is overhead an untapped and vast natural low-cost cooling resource: the clear night sky.

The ERM methods proposed in this review address the same type of outgoing longwave radiation that the GH effect keep trapped; meanwhile the SRM addresses incoming solar shortwave radiation. Thus even if SRM can on average reduce the temperature in similar proportions as the increase caused by the GH effect, the effects will be for instance more precipitation in some parts of the Earth and more droughts [112] elsewhere, with losers and winners. If unintended effects appear and if it becomes necessary to provide food to the local population, or if logistical support is needed, or if financial compensation or reconstruction are necessary, then the costs of SRM and of GE will keep growing up. Meanwhile building for instance SCPPs in desert countries with local labor and materials will provide work, growth, economic development and welfare and also benefits to the investors. Agricultural greenhouses in the middle of deserts can be filled with cold humid air coming out from DETs and irrigated with desalinated water produced in synergy at proximity.

This paper shows that geoengineering is not the last resort against global warming and that other strategies might help to solve the current problems without the need to just buy time by relieving GW symptoms without addressing the ocean acidification problem, nor the CO_2 accumulation in the atmosphere. Instead of setting a sunshade for planet Earth like the techno-fix described in the 4th episode of the “Highlander” movies, other solutions might be possible. SRM try to solve the CO_2 problem without decreasing CO_2 releases. ERM proposes taking control of our planet's climate by unusual power generating systems producing CO_2-free renewable energy allowing heat loss into space and helping to cool the Earth's surface. Instead of trying to counteract a longwave radiation trouble by different shortwave radiation strategies, ERM works on the longwave radiation part of the spectrum with MR based on thermodynamic properties of the Earth's atmosphere, reproducing several natural phenomenon and the water cycle. This timely composed review should stimulate many more research teams and hopefully it will be useful not only to the technical community, but also to policy makers and power industrial firms to enter the exciting field of ERM and to push it forward to diverse practical applications.

Investment in renewables, in UREs and in a sustainable economy is not only a worthwhile cause but has also economic value. The associated carbon credits would also help offset the carbon liabilities for normal operation and hence add to the economic viability of sky cooling, UREs and MR.

14. Conclusion

In this review the main GE methods proposed to perform SRM in order to reduce the effects of anthropogenic global warming were summarized, and some of their limitations introduced and ethical aspects reported. Before introducing the concept of ERM, a short review of the literature showing that anthropogenic waste heat release by thermal power plants might be important at a local scale was given, as well as a short overview of some drawbacks of several renewable energies, which makes them "not so green" or "not so neutral" for the climate change problem.

Then this review paper proposed several new concepts aimed to fight global warming by enhancing outgoing longwave radiation, and able to transfer heat out to space, prevent sea level rise and avoid future costs, for instance of hurricanes, or of CCS or CDR. In this purpose, power-generating systems able to transfer heat from Earth to upper layers of the atmosphere and then to the space are reviewed. The individual UREs presented in this paper were initially developed to become power plants for decarbonized electricity production. The principal new concept proposed in this paper is that it is possible to increase the longwave radiation transfer from the Earth surface to the outer space by increasing the direct energy transfer from the Earth to the space by the atmospheric window; transferring surface hot air in altitude; transferring cold air to the surface; transferring heat from the oceans in altitude; increase sea ice thickness. So these UREs can be named meteorological reactors. This article shows that a large family of MR exist, ant that these MR are able to manage longwave radiation in order to cool down the earth.

SRM is not intended to solve the climate change problem. SRM is intended to buy time to let our descendants or heirs find the solution for us, address it latter and pay for it. The world population growth, growth per capita, carbon intensity growth and the economic development require more energy. SRM does not provide more energy to humanity. SRM does not stop the inadvertent climatic change due to fossil fuels combustion. The IPCC conclusions can be summarized to the fact that all climate models demonstrate that the best way to stop climate change is to stop the introduction of CO_2 in the atmosphere. SRM allows more CO_2 accumulation in the atmosphere. SRM is a voluntary and targeted climate modification. On the contrary ERM consists in a voluntary reduction of the main cause of climate change as a large scale deployment of MR decarbonizes the economy, is able to provide the humans the energy they need and can help to cool the Earth surface and curb GW.

Hansen [106] performed computer simulations of the equilibrium responses in case forcings are introduced in the higher layers of the atmosphere: the higher the heating is introduced, the larger is the fraction of the energy that is radiated directly to the outer space without warming the surface. Simulations performed by Ban-Weiss [111] showed that for every $1\,W\,m^{-2}$ that is transferred from sensible to latent heating, on average, as part of the fast response involving low cloud cover, there is approximately a $0.5\,W\,m^{-2}$ change in the top-of-atmosphere energy balance (positive upward), driving a decrease in global mean surface air temperature. Other models [186] assimilate the tropical cyclones to Carnot heat engines that absorb heat from a warmer reservoir (the ocean surface) and reject a fraction of it to a colder reservoir (the highest atmospheric layers of the troposphere and thus the outer space) while doing work.

One of the ideas developed in this review is that GHGs are too good insulators that prevent normal interactions between the Earth atmosphere and the outer space and thus keep the Earth too hot, so atmospheric thermal bridges have to be created. For this purpose, the rupture technology concept of meteorological reactors is given: these are unusual power plants able at the same time to produce renewable and clean energy, avoiding future CO_2 emissions, reducing hurricane intensity, preventing heat waste release at the surface level and cooling down the Earth by increased sensible heat transfer or latent heat transfer out to space.

A combination portfolio of techniques, an energy mix of a wide large bunch of methods that are free of CO_2 emissions will be necessary to fight global warming. Meanwhile current power plants release heat at the surface, MR release it in altitude and can at least contribute to cool down the Earth surface and help it to keep a neutral global energy budget.

The accelerated technology scenarios explored by the IEA [95] suggest that even a major global mitigation program, based on successful development and deployment of several new technologies, will still allow substantial global warming by 2100.

Availability of key technologies will be necessary but not sufficient to limit CO_2 emissions. Mitigation of three trillion tons of CO_2 by 2100 is deemed a serious goal, thus a major increase in R&D resources is needed. Given the monumental challenge and uncertainties associated with a major mitigation program, the authors would like to advise to consider all available and emerging technologies. This suggests fundamental research on new MR energy technologies in addition to those already known in order to become part of the global research portfolio, since breakthroughs on today's embryonic technologies could yield tomorrow's alternatives.

The authors hope that the ideas exposed in this paper might help this purpose and that in the near future, by their capability to supply massive amounts of energy carbon emission-free and for their prospective for large-scale implementation some UREs described here will give a significant contribution to the overall solution to global warming, although they still require more research, but first and foremost much more investments to build the first industrial plants as the theoretical assessment is already rich and almost complete.

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